ATLAS-LHCf neutron analysis for the Run2 data

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ISEE Nagoya Univ. (~2023 Feb.)-> LHEP, University of Bern (2023 Mar.~)

Status

Most parts finished, but still several points to be updated

- Before I left Nagoya this February,
    - The draft of the analysis note was uploaded.
    - Analysis, but several missing parts
    - I’m now working on the FASER experiment at University of Bern, but also very slowly updating this analysis.
- Most parts of the analysis were finished but
    - Validation of analysis procedure using ATLAS-LHCf full simulation
    - A correction factor of detection efficiency
        - Eugenio did an analysis.
        - I need to implement it in the analysis
    - Internal note
        - I made a draft, but no comments from the ATLAS side.
- Works not finished before this February
    - Several minor updates of calculations
    - Cross-check of the detection efficiency of LHCf detector
    - Validation of all procedures of analysis using ATLAS-LHCf common simulation instead of experimental data.
    - Analysis note

Motivation of analysis

Multi-parton interaction

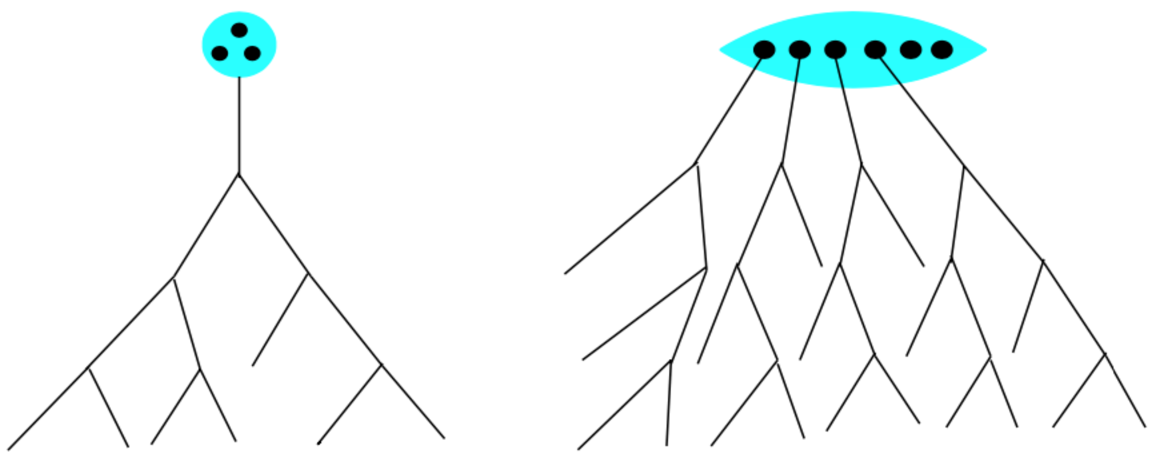
The modeling of multi-parton interaction (MPI) affect central-forward correlation.

Proposed by S. Ostapchenko et al, Phys. Rev. D 94, 114026

Initial part of Parton cascade are modeled as :

universal state (PYTHIA and SIBYLL)

superposition of partons (EPOSLHC and QGSJET II).

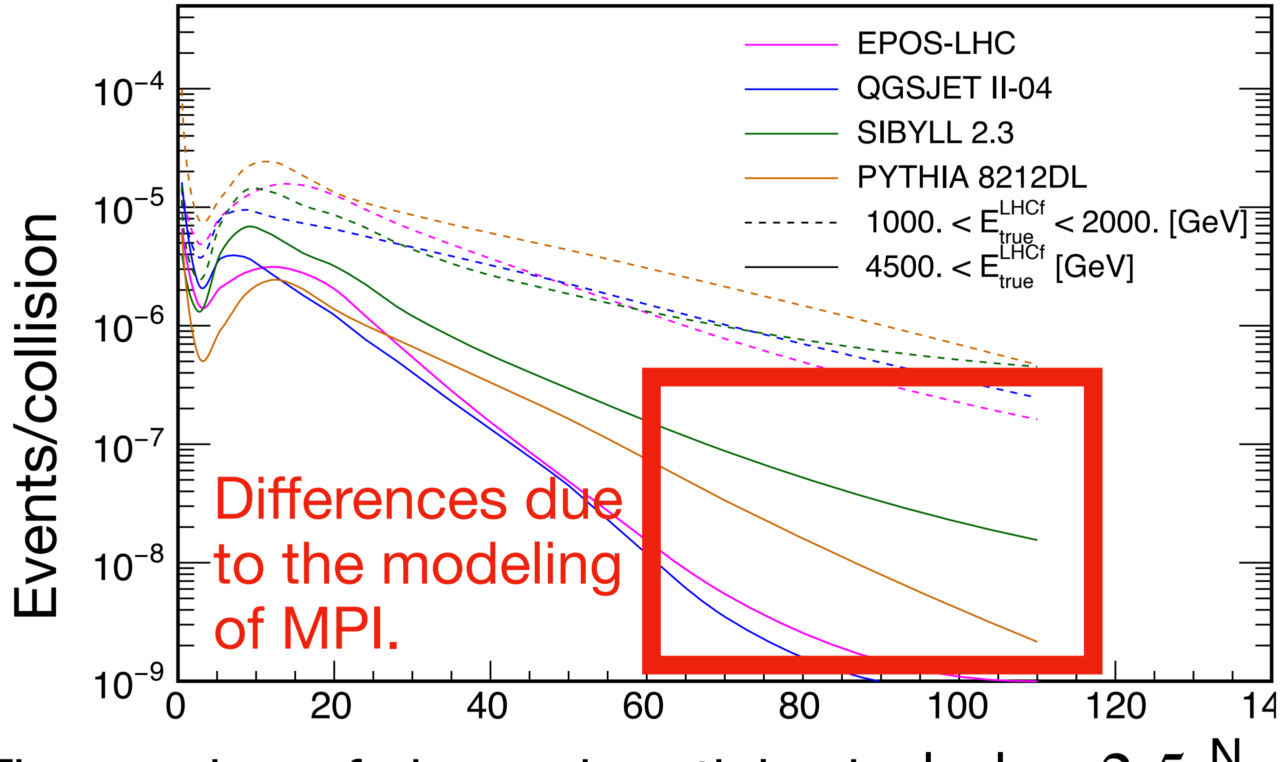


Remnant energy - number of MPI correlation:

Small — Large

The number of multi-patron interactions -> N_{ch}

The energy of <u>remnants</u> -> neutrons in LHCf



The number of charged particles in $|\eta| < 2.5$

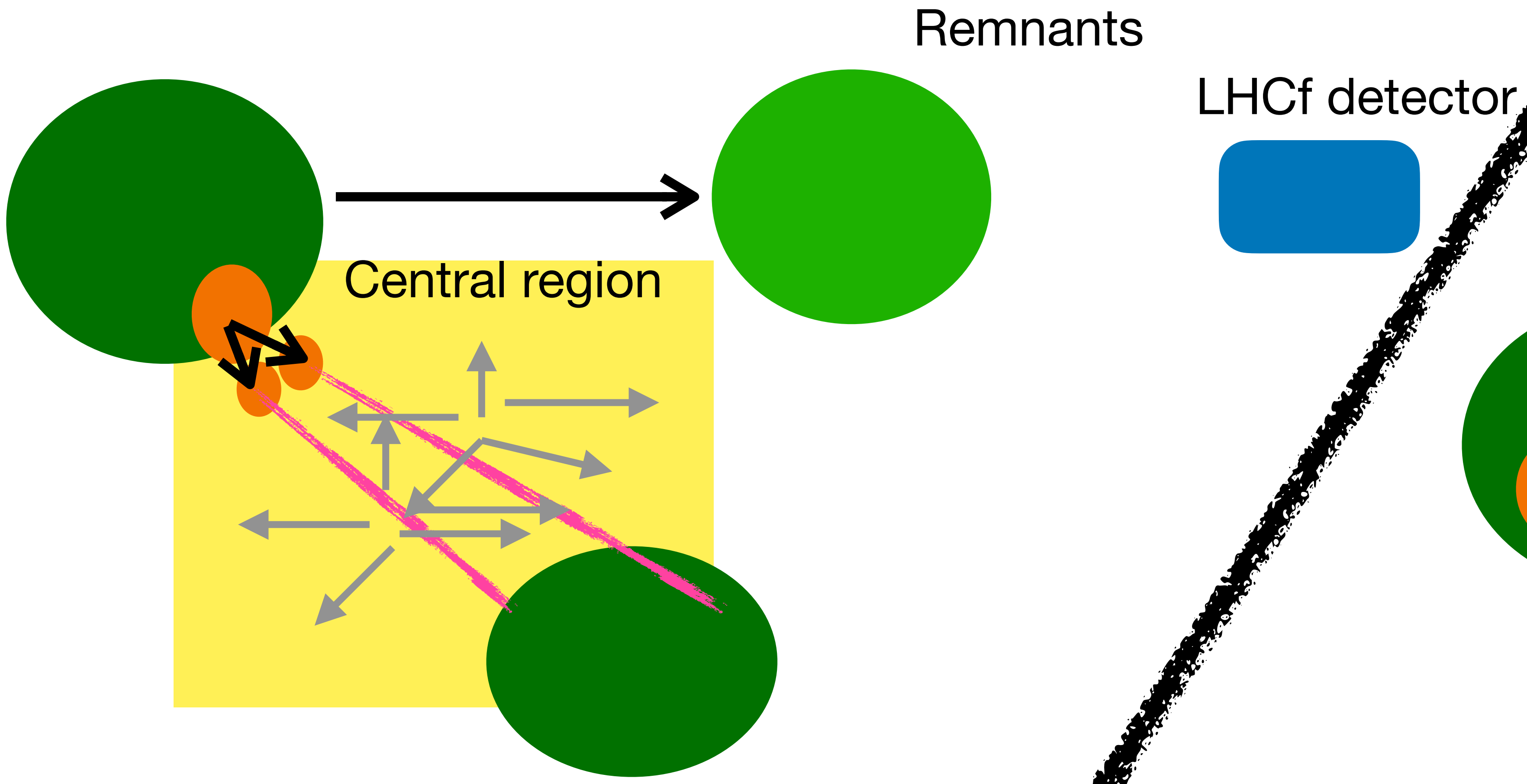
EPOS-LHC and **QGSJET** predict strong central-forward correlation; if high energy neutrons are measured by the LHCf detector, the number of high N_{ch} (high MPI) events is very small.

On the other hand, **SIBYLL 2.3** and **PYTHIA** show weaker central-forward correlation.

Two parton interactions for example

<u>Based on explanations by T. Pierog.</u>

A: PYTHIA and SIBYLL

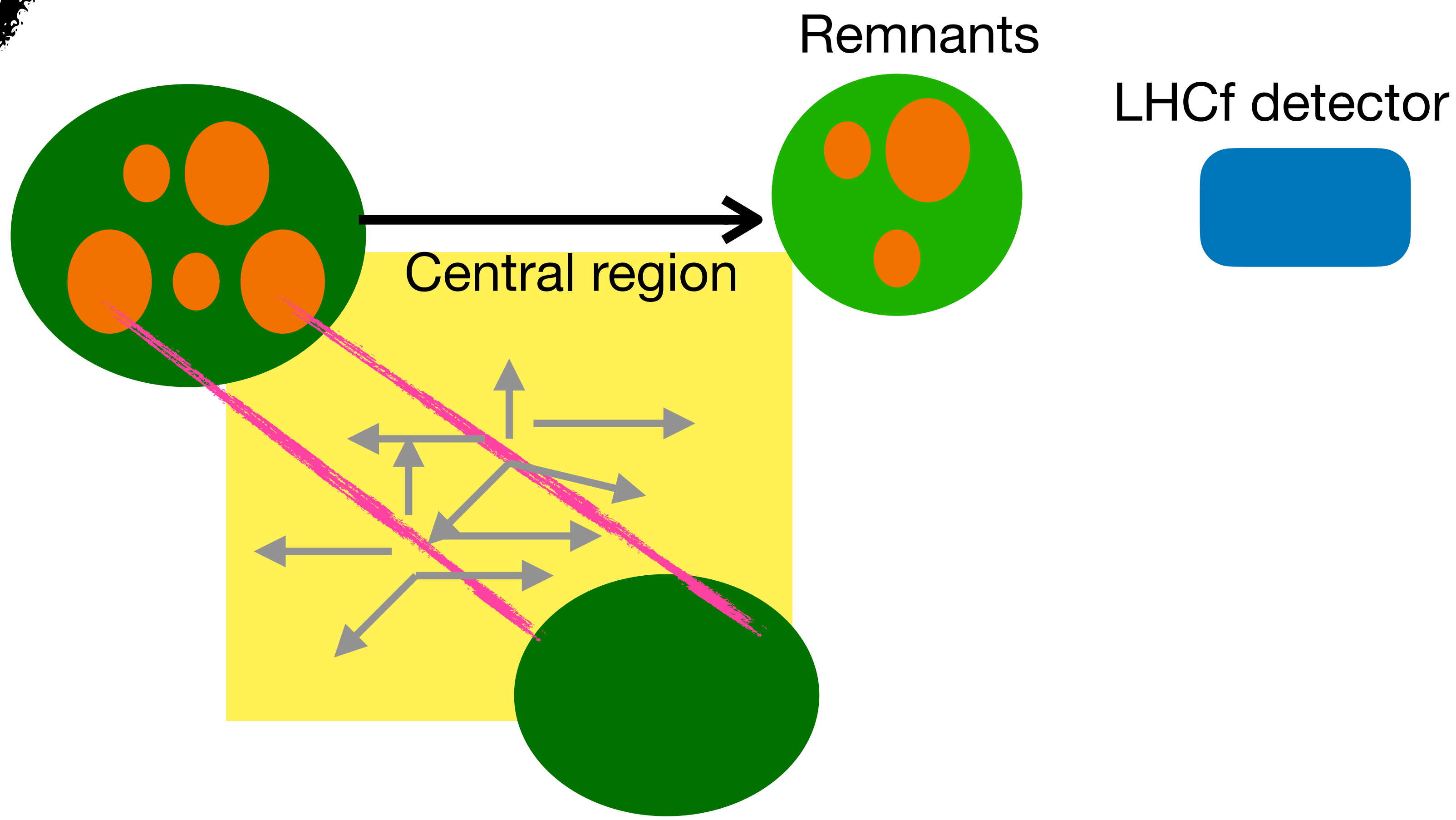


Two parton interactions share the energy of parton.

Motivated as total of MPI energy is calculated from kinematic overlapping of pp

B: QGSJET and EPOSLHC

Each parton interaction is associated with a parton.

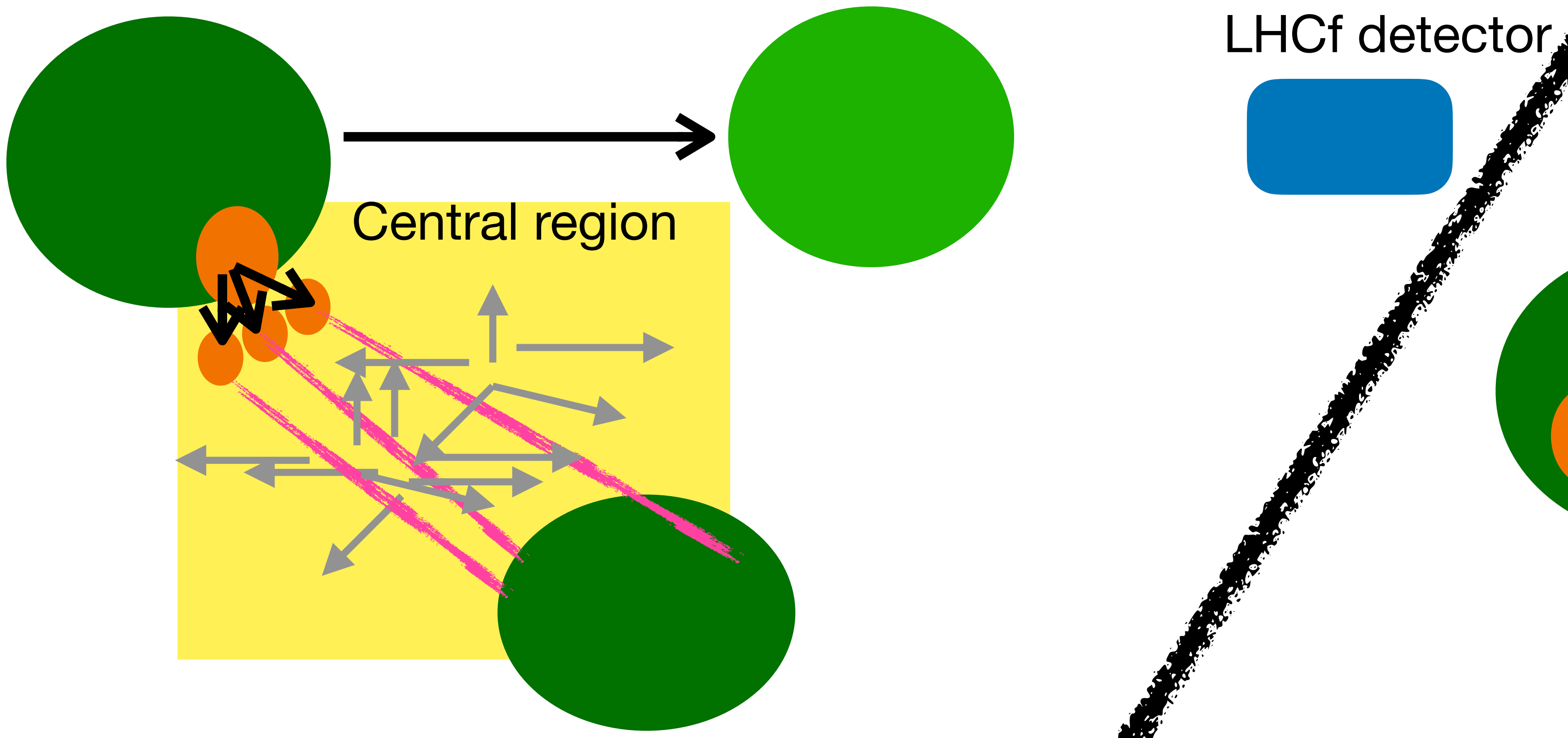


Motivated as MPI is superposition of independent parton-parton interactions.

Three parton interactions for example

Based on explanations by T. Pierog.

A: PYTHIA and SIBYLL

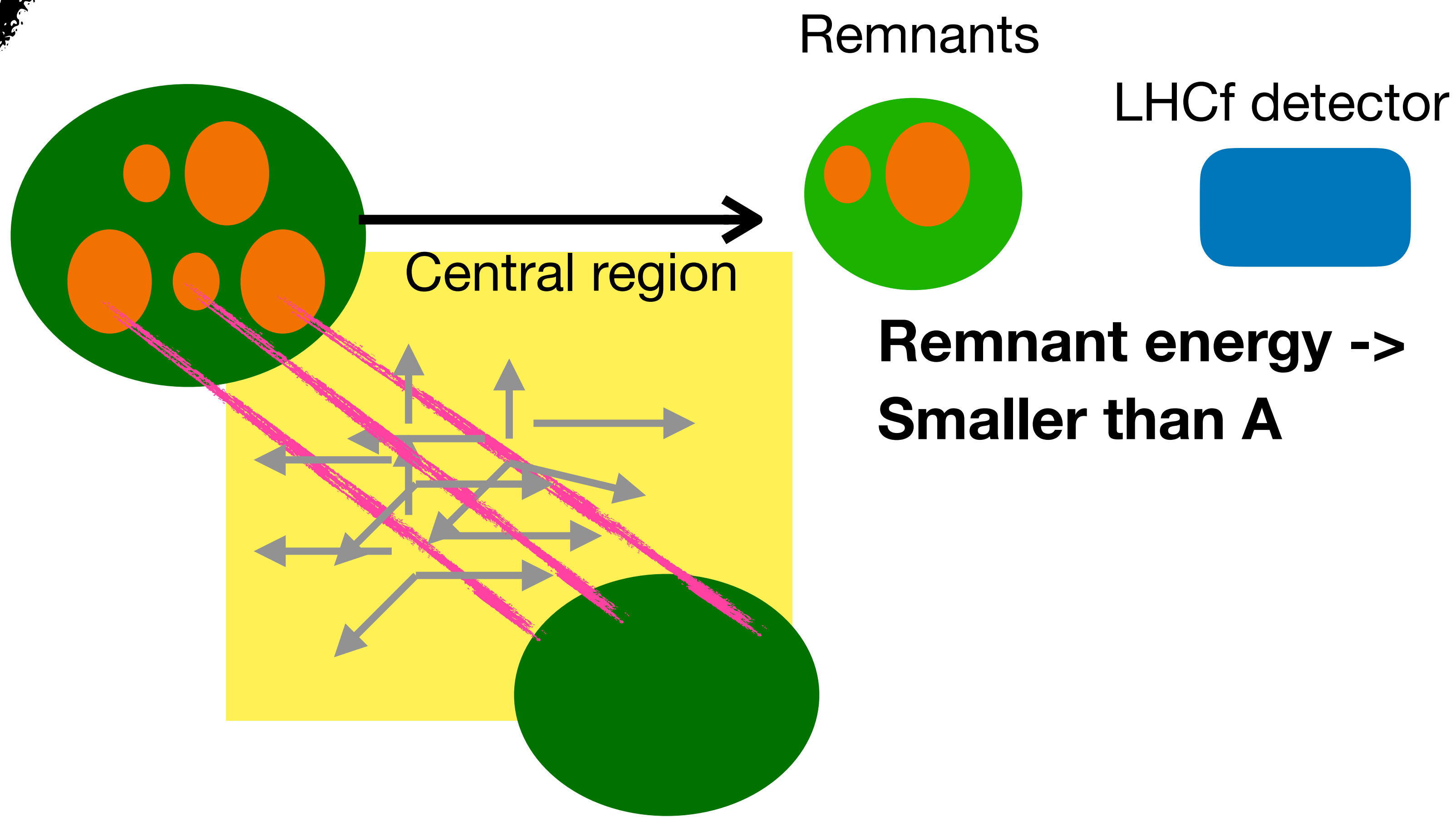


Three parton interactions share the energy of parton.

Energy transferred into central region defined by the energy fraction of one emitted parton.

B: QGSJET and EPOSLHC

Each parton interaction is associated with a parton.



Remnant energy -> Smaller than A

Energy transferred into central region correlated with the number of interacting patrons (= number of MPI)

Analysis strategy

ATLAS-LHCf Run2 data analysis

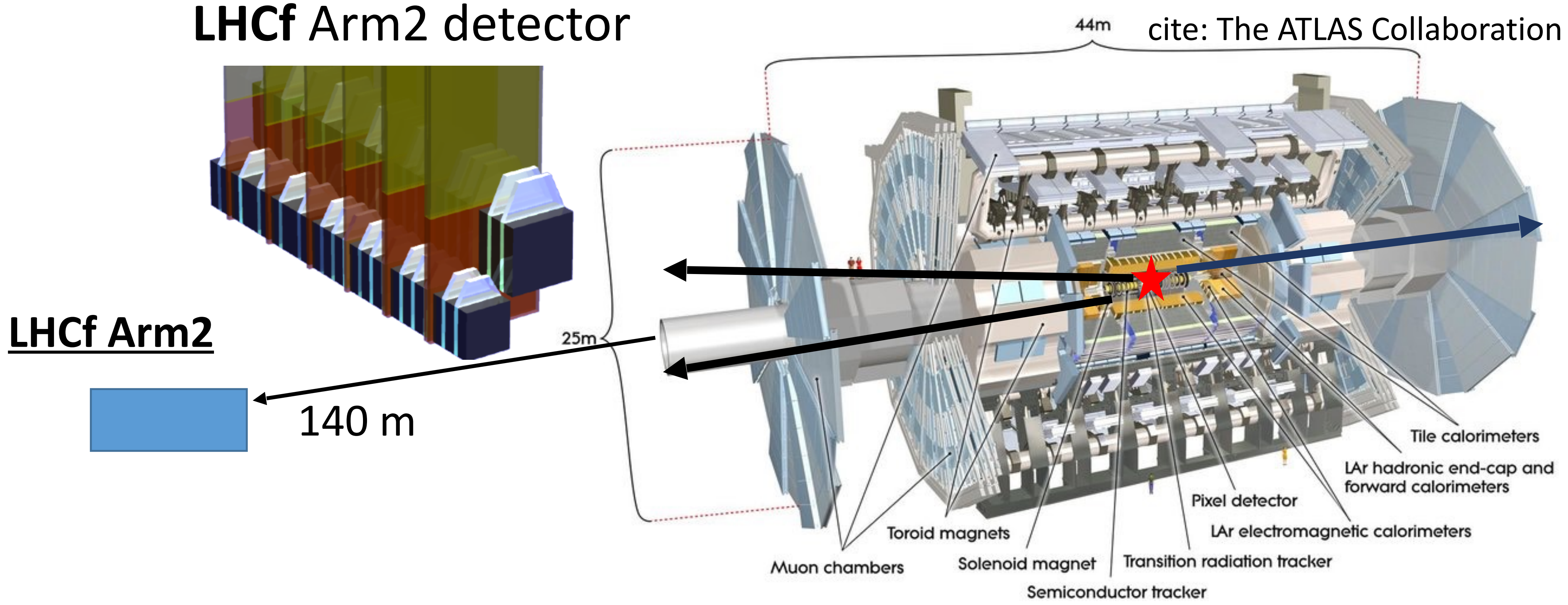
Detector

LHCf: LHCf Arm2

Neutrons with contamination of K0 and Λ

ATLAS: inner tracker

The number of tracks made by charged particles



Dataset:

Taken in 2015. $\sqrt{s}$ = 13 TeV.

(from 22:32 to 1:30 (CEST) on June 12-13, LHC Fill 3855)

$L_{int} = 0.191 \pm 0.4\,\mathrm{nb}^{-1}$

MC:

Full simulation: 10^8 collisions (QGSJET), 5×10^7 collisions (EPOSLHC)

Collision + propagation: 10^9 collisions (QGSJET, EPOSLHC, SIBYLL 2.3, PYTHIA 8.212DL)

Artificial MC for the Multi-hit correction factor.

Fiducial regions of the analysis

Fiducial regions

N_{charged} in $|\eta| < 2.5$: $10 \leq N_{\text{charged}} < 80.$

Energy of hadrons :

Neutral hadrons with $E > 1$ TeV in $8.99 < \eta < 9.22$ (Region 1) or $8.81 < \eta < 8.99$ (Region 2)

At 140 m from interaction points

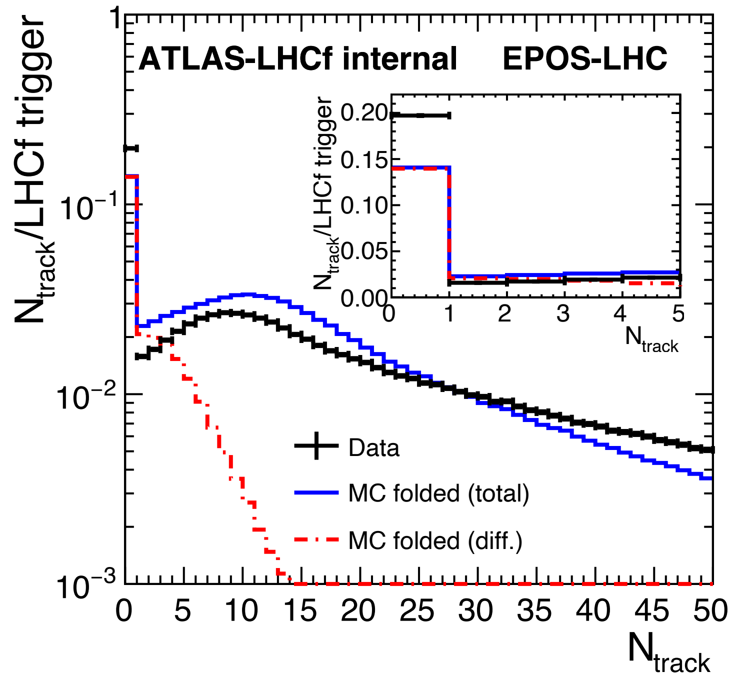


Figure from analysis note for photon analysis

definition of N_{track} was changed.

Black : experimental data.

Red : diffraction (MC)

Blue : all (MC)

In analysis, to consider migrations,

N_{track} in ATLAS inner tracker : $2 \leq N_{\text{track}} < 140$

Energy of hadrons in LHCf :

Hadron-like events with $E_{\text{reconstructed}} > 250$ GeV in $8.99 < \eta < 9.22$ (Region 1) or $8.81 < \eta < 8.99$ (Region 2)

for LHCf-Arm2 detector

Analysis procedure and updates from the last report

Analysis procedure

Event selection

- LHCf detector
  - Hadron-like events using PID
  - $E_{rec} > 250\,\mathrm{GeV}$
  - No multi-hit event selections
- With the number of tracks in ATLAS inner tracker
  - p_T > 0.1 GeV/c, D0 < 1.5 mm
  - “good tracks” definitions
    - Primary vertex, Z0, number of pixel hit etc.

Correction

Background
- Collisions with gas in beam pipe
- Beam pipe materials

LHCf related
- Particle ID correction
- Multi-hit correction
- Position migration correction
- Fake events in LHCf
- Contaminations

After unfolding
- Miss events in LHCf

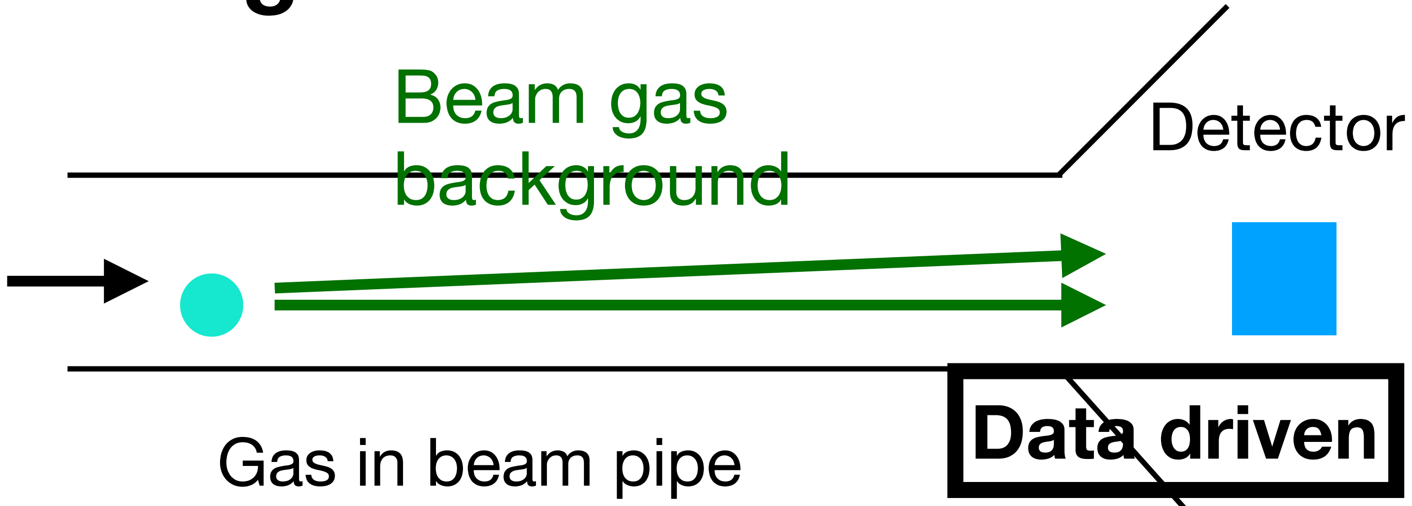
Unfolding

$$(E_{rec}, N_{track}) \rightarrow (E_{true}, N_{ch})$$

The method developed in LHCf-Arm2 analysis was implemented.

Correction factor

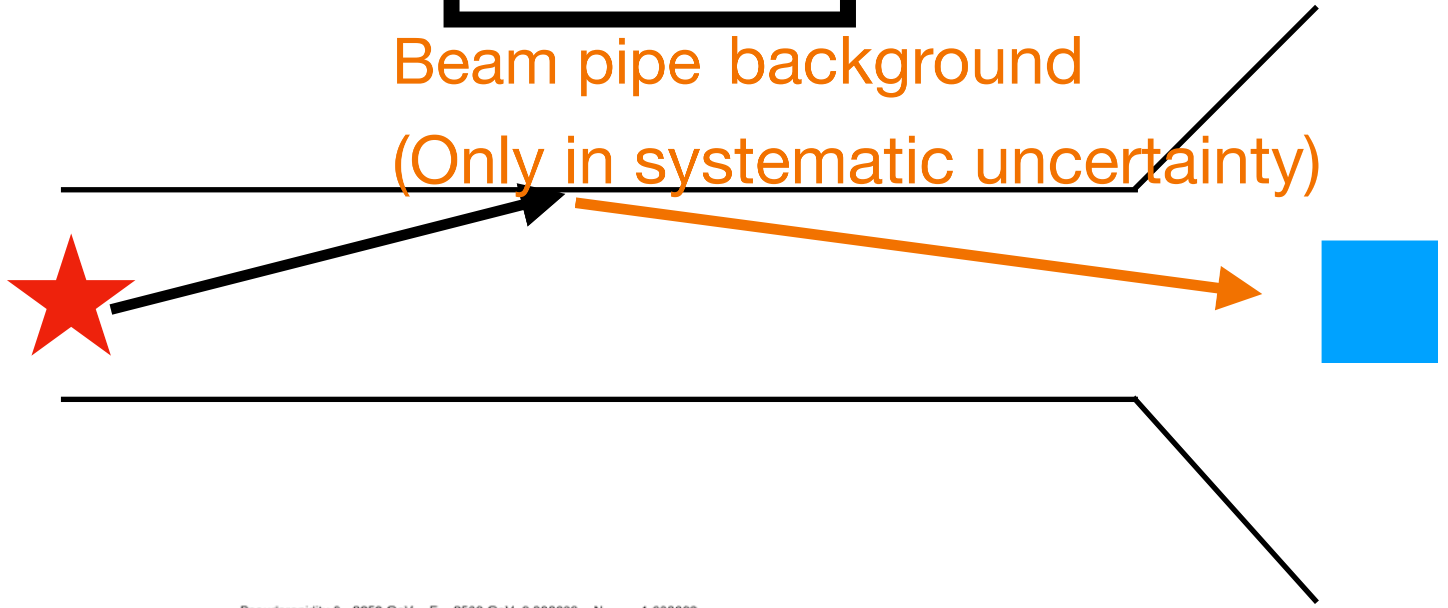
Background Correction



Gas in beam pipe
Estimated using non-colliding bunch

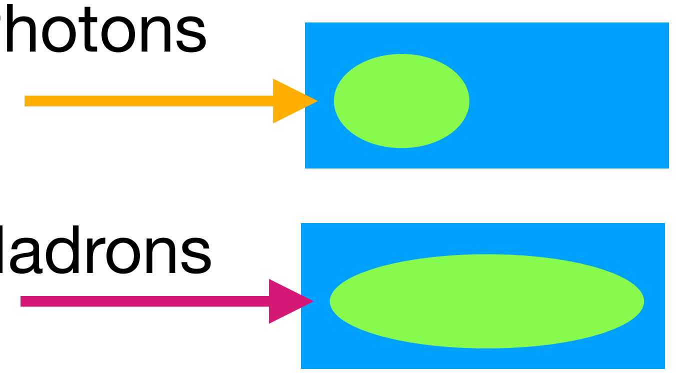
MC driven

Beam pipe background
(Only in systematic uncertainty)



Particle ID

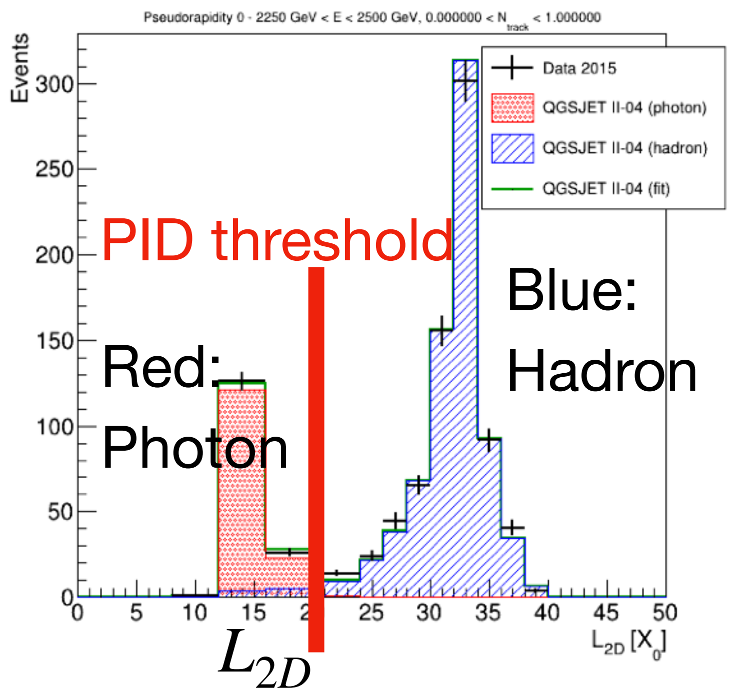
Data + MC (fitting)



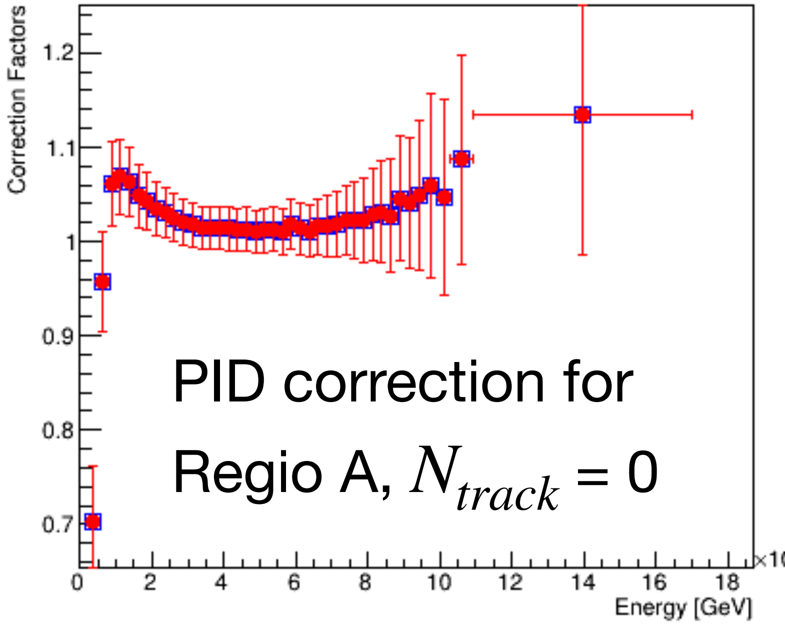
Template fitting of experimental data

Purity and efficiency of PID event selection

PID correction factor



Parameter of the depth of the shower developments.



Reconstructed energy [GeV]

Correction factor

Position migration, fake/miss

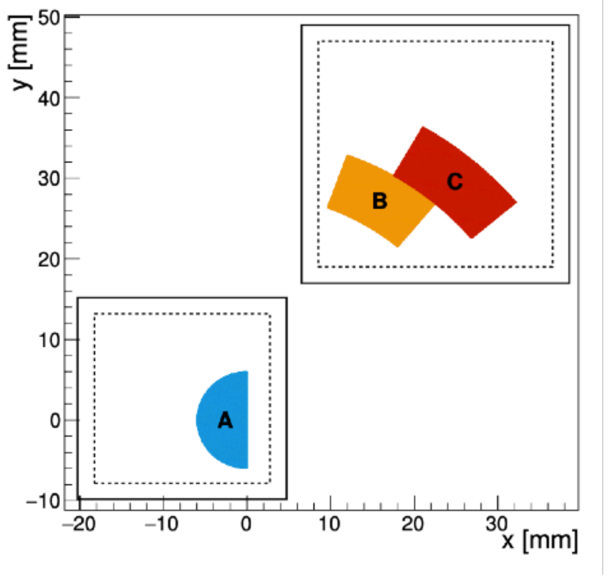
MC driven

Position migration

Migration due to the position resolution

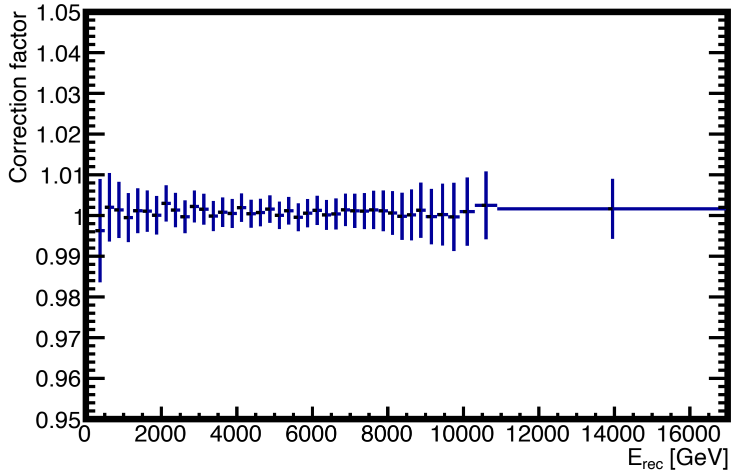
Position resolution; 100 μm for > 3TeV

Three analysis region



Position migration correction for

Region A, $N_{track}=0$



Reconstructed energy [GeV]

Fake correction

Fake events due to 250 GeV energy cut and energy resolution.

Miss correction (apply after unfolding)

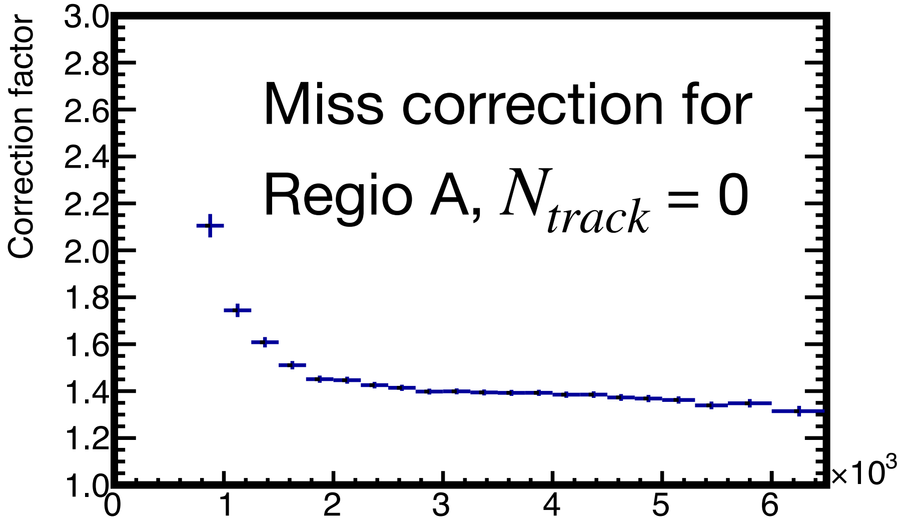
Events without interactions in the detector.

(LHCf detector: 1.6 interaction length,

~ 20-30% events are without interactions

at high energy)

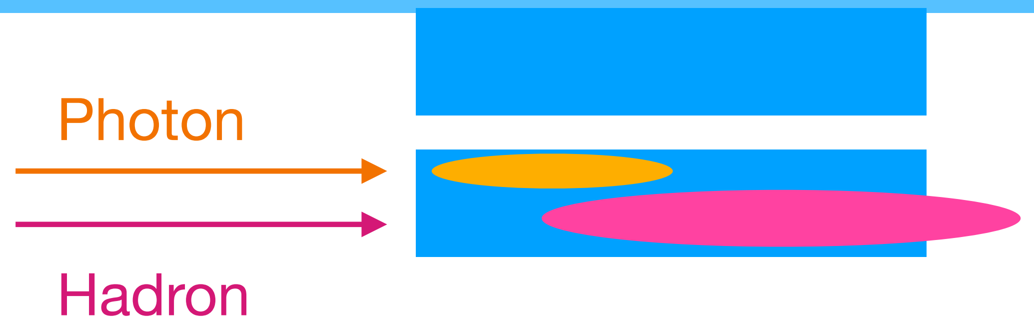
And miss events due to energy threshold cut



True energy [GeV]

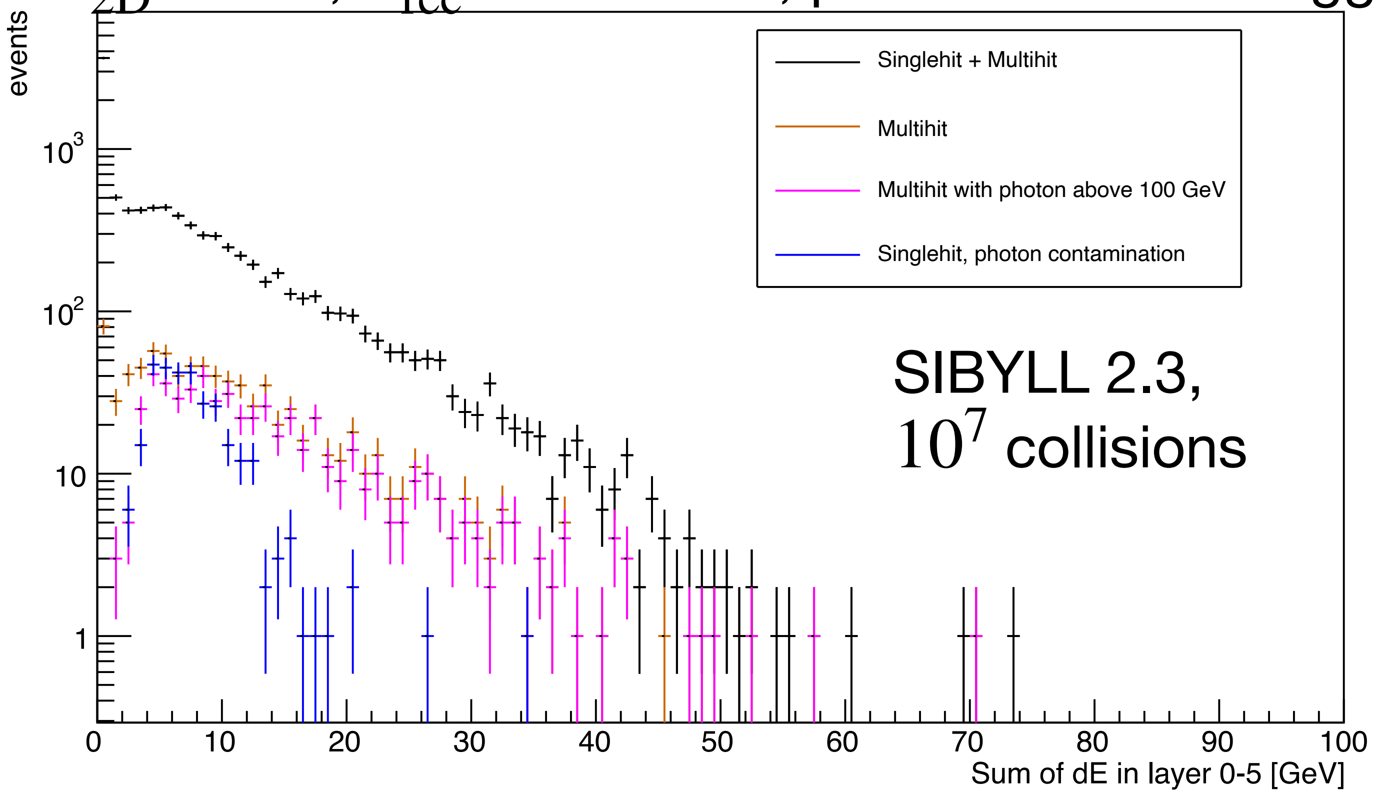
Correction factor — Multi-hit correction

MC tuning using the multi-hit reduced sample

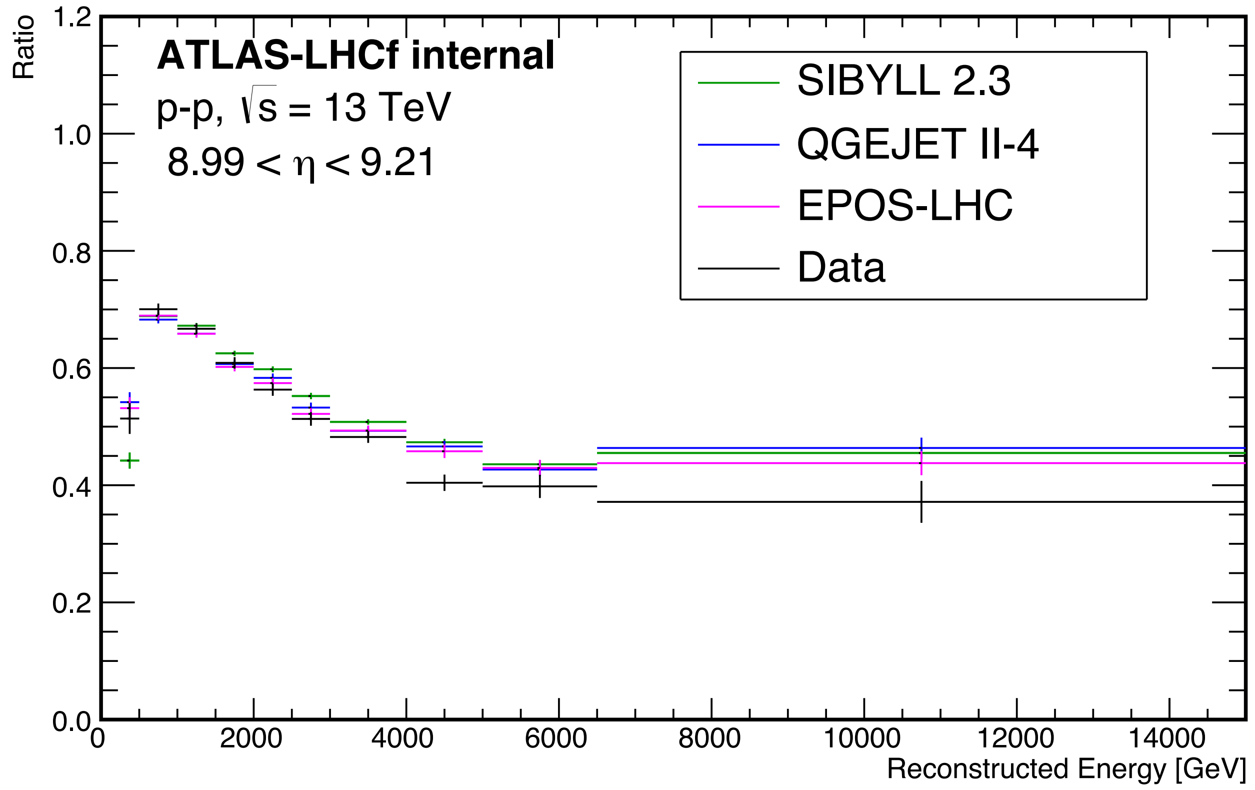


Photon + hadron multi-hit events have larger signals in the first 6 layers.

Large tower, Region 1 (by reconstructed positions),
$L_{2D} > 25., E_{rec} > 250$ GeV, passed software trigger



Ratio = (multi-hit reduced)/(nominal spectrum)



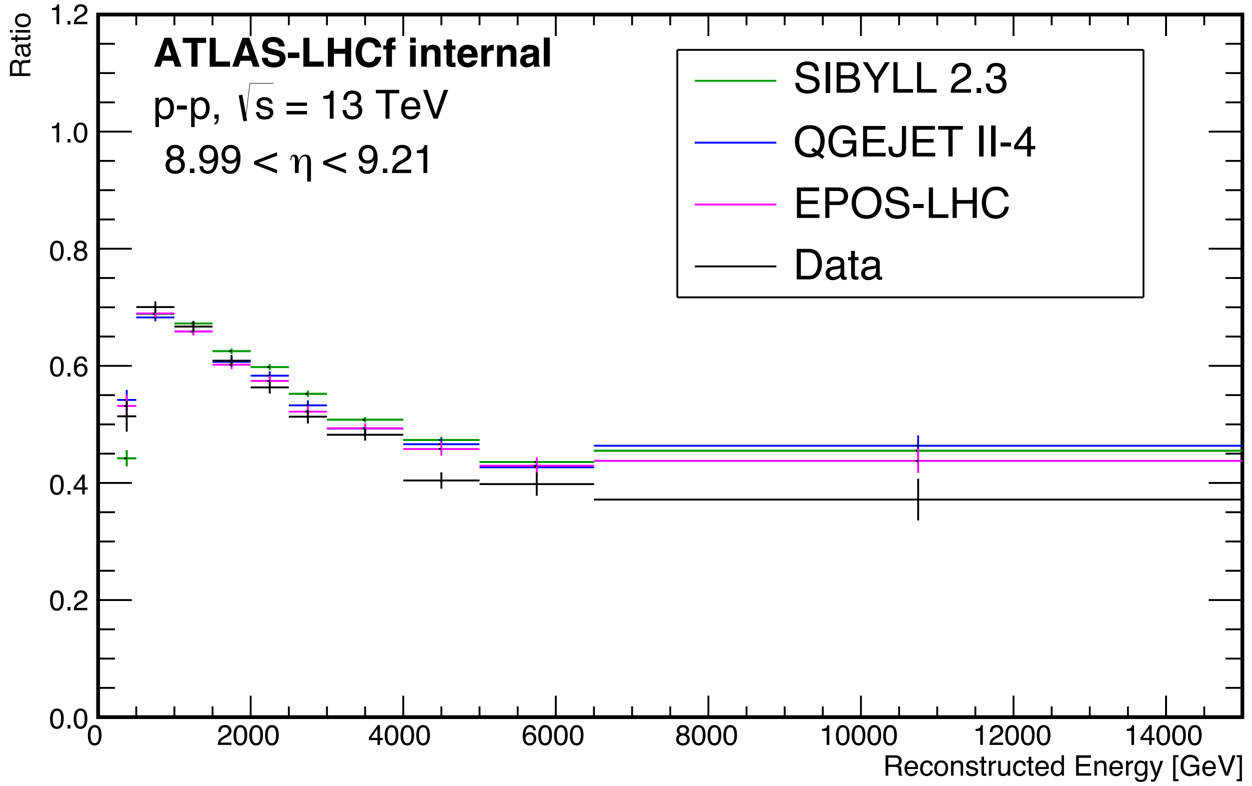
Multi-hit reduced samples by selecting (sum of dE in the first 6 layers) < 3.0 GeV

-> Calculate the normalization factor for multi-hit events from experimental data

Template fitting

Ratio of multi-hit reduced to inclusive

Large tower, Region 1 (by reconstructed positions),
$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger



Minimizing the following value

$$\sum \frac{(R^{\mathrm{data}} - R^{\mathrm{MC}})^2}{\sigma^{R^{\mathrm{data}}} + \sigma^{R^{\mathrm{MC}}}}$$

$$R^{MC} = \frac{\alpha N_{\mathrm{cut}}^{\mathrm{single-photon}} + \beta N_{\mathrm{cut}}^{\mathrm{single-hadron}} + \gamma N_{\mathrm{cut}}^{\mathrm{multihit}}}{\alpha N^{\mathrm{single-photon}} + \beta N^{\mathrm{single-hadron}} + \gamma N^{\mathrm{multihit}}}$$

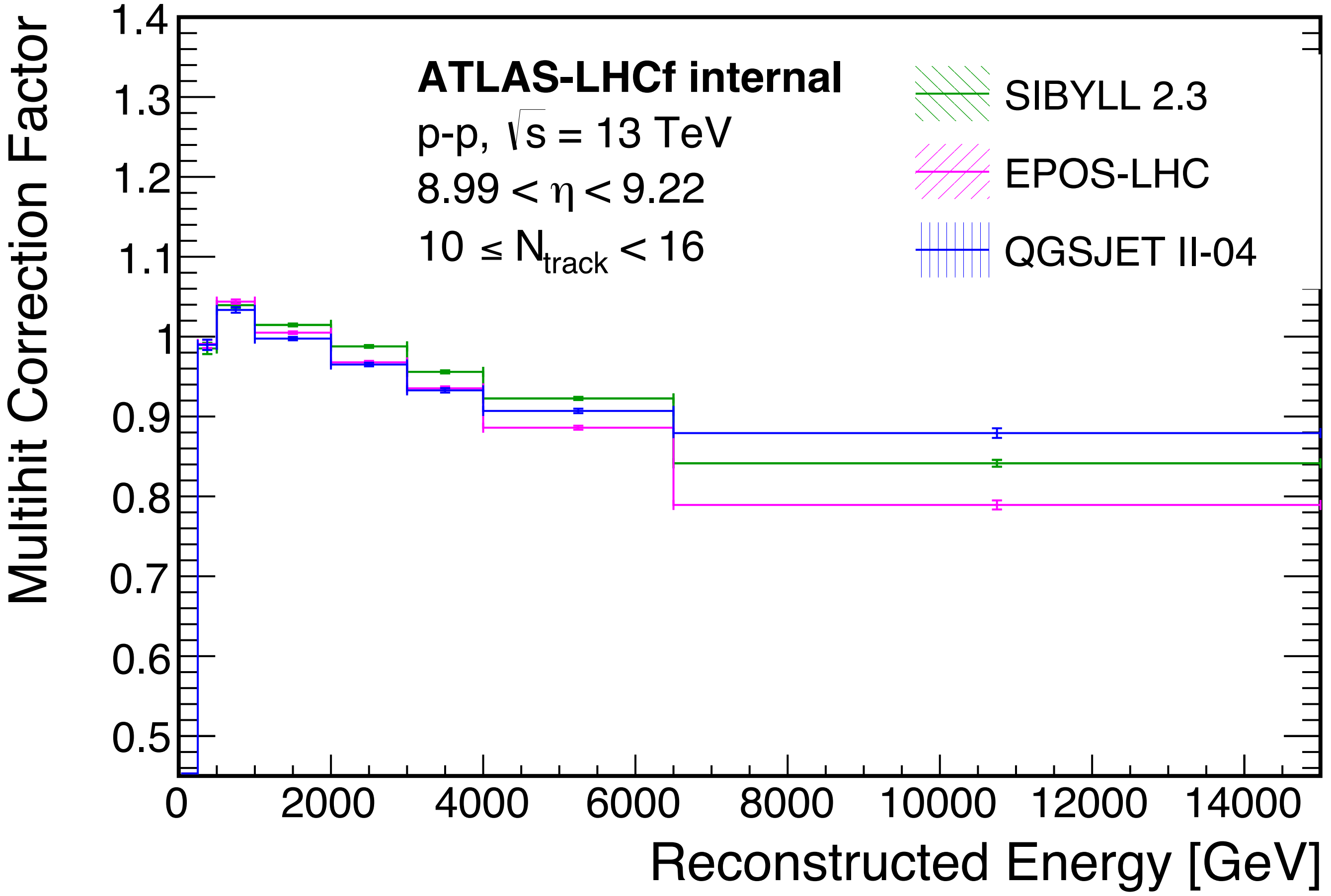
Parameter β is fixed to 1.0

Apply data-driven factors

Multi-hit correction after applying the data-driven normalization factor

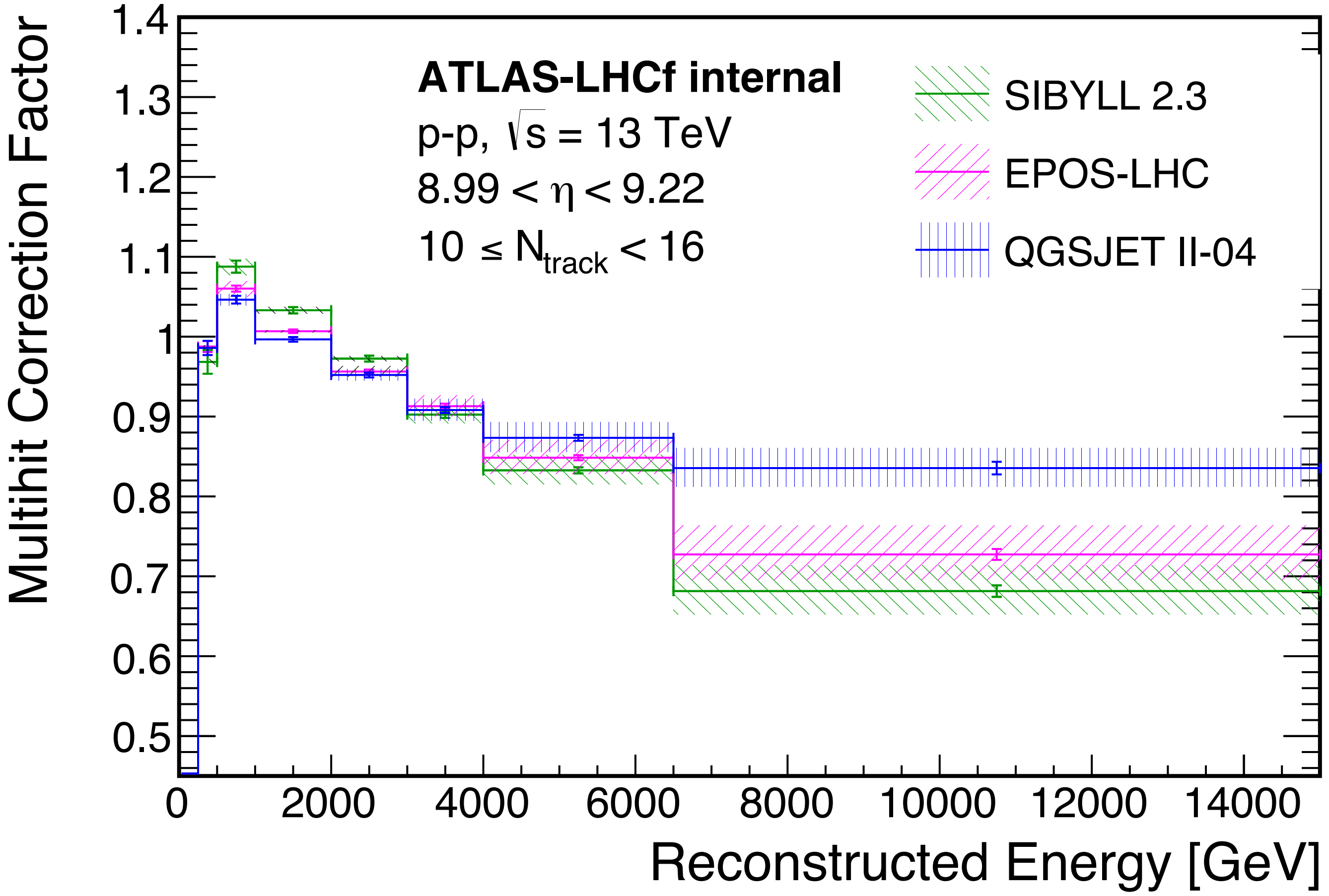
Region 1

No factor applied



Hatched regions: considering errors in factors

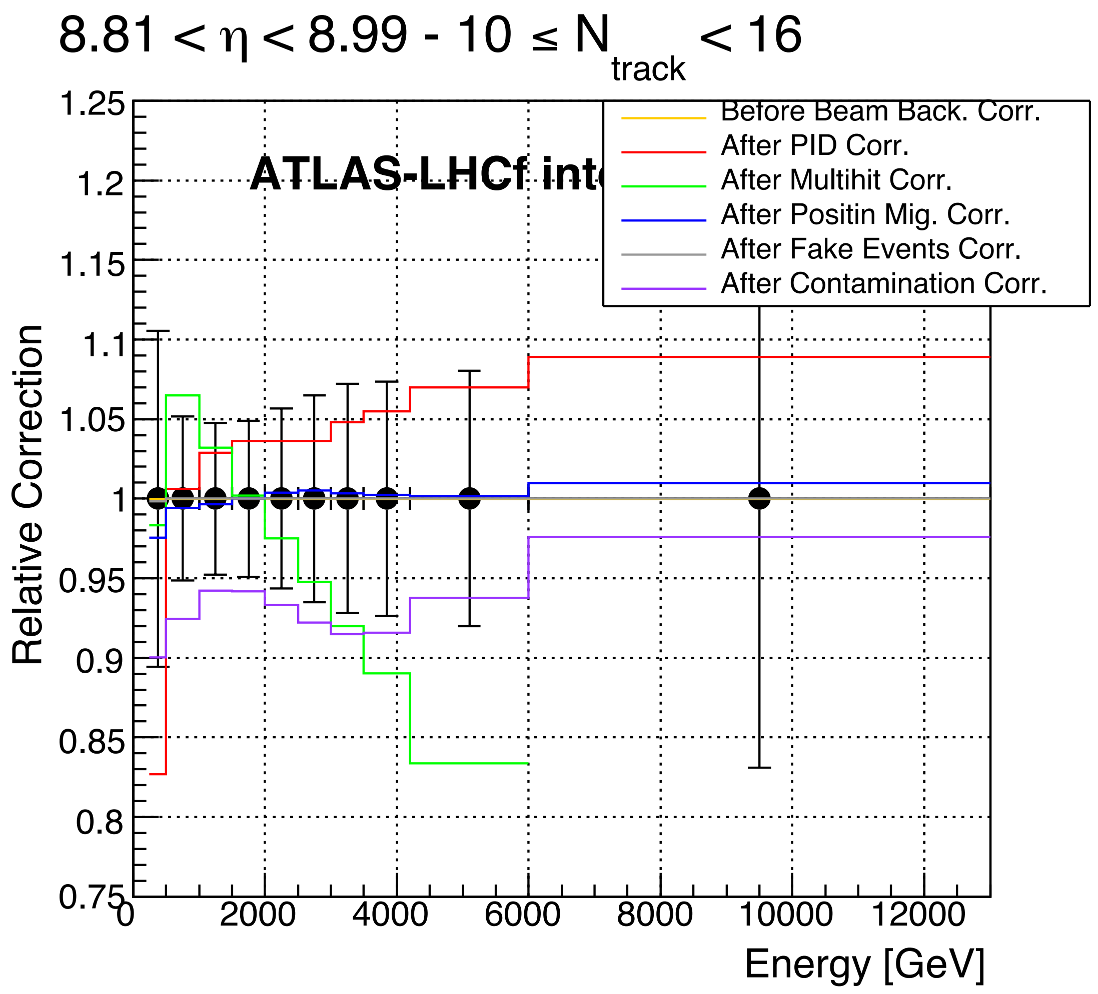
Error bar: statistical errors of MC.



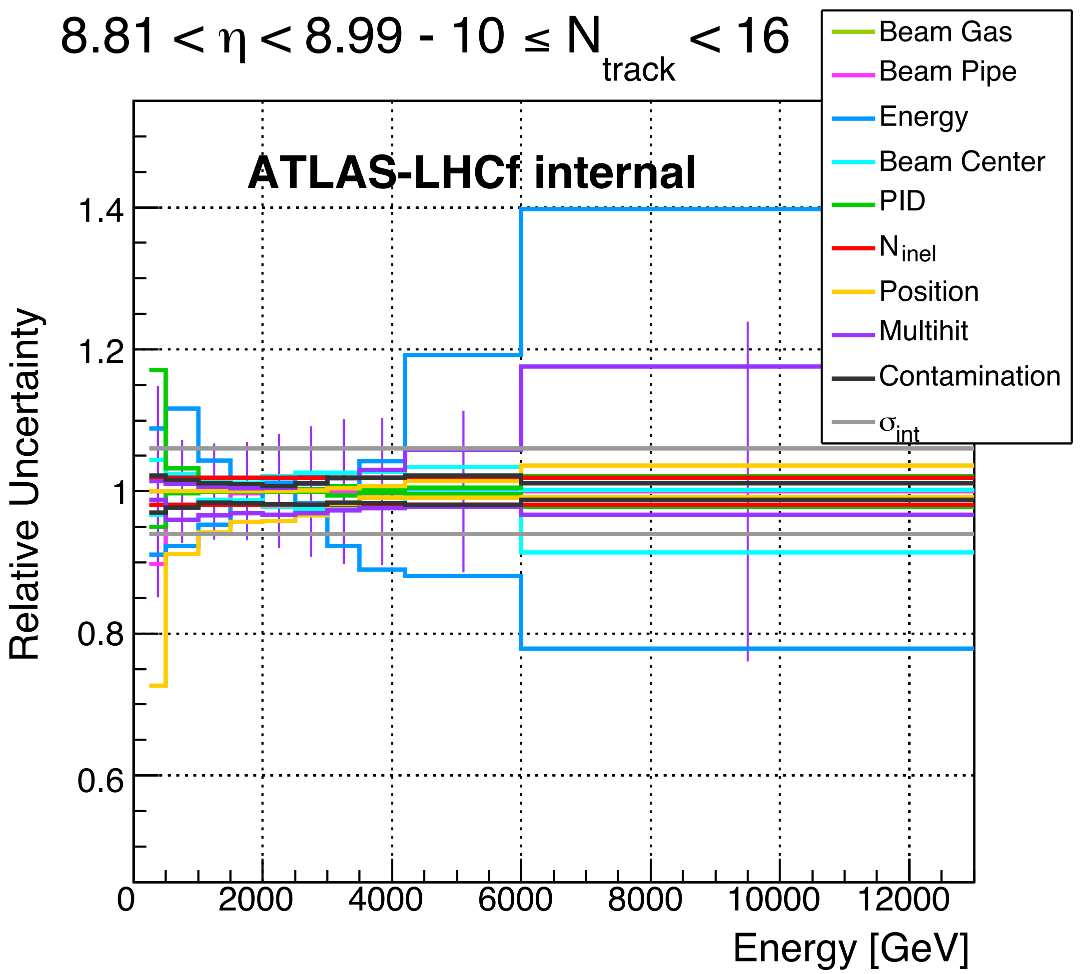
Status of corrections and systematic uncertainties

Results before unfolding

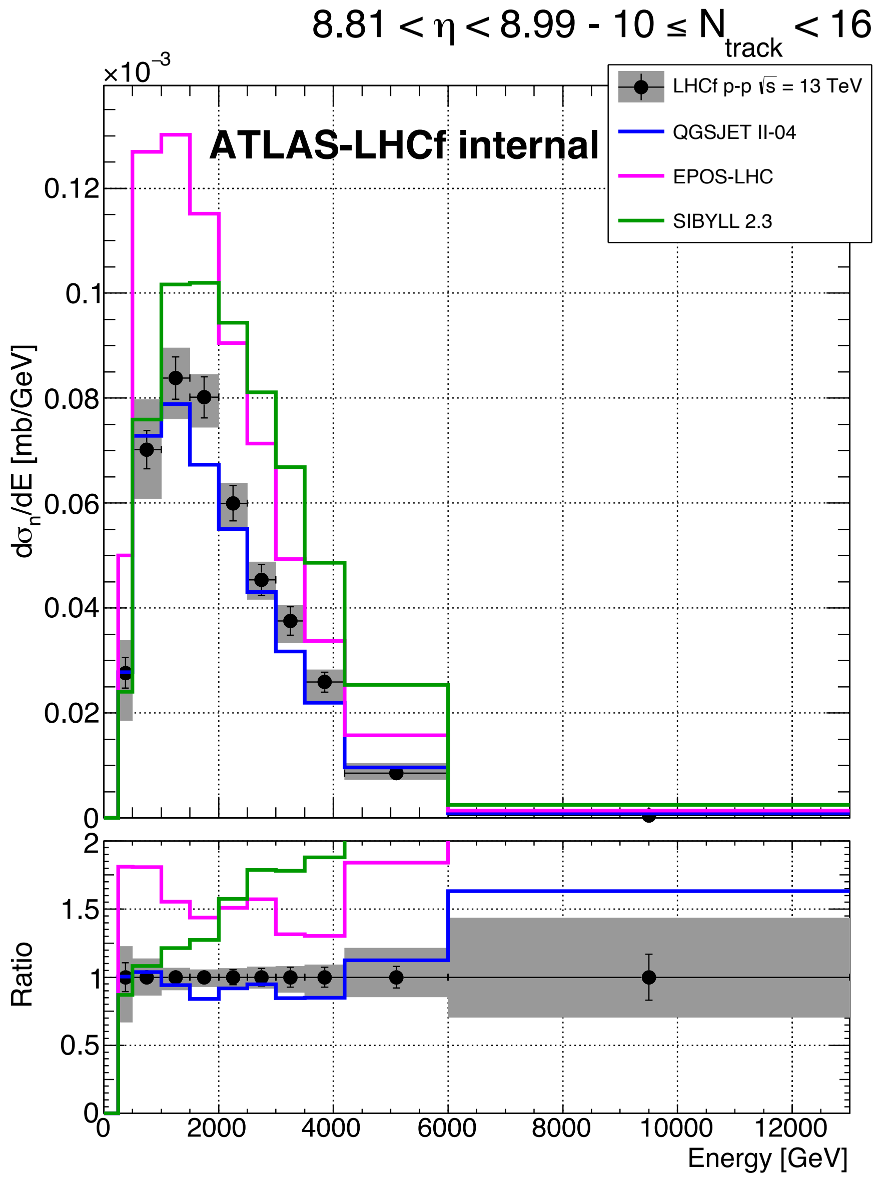
Correction factors



Systematic uncertainties



Spectrum before unfolding



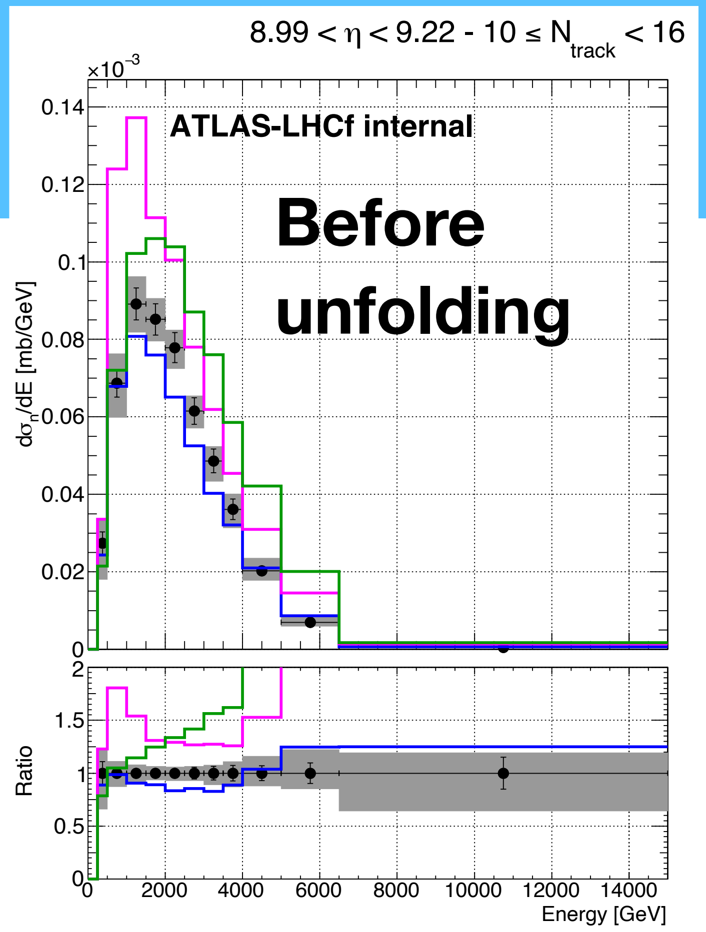
Details of analysis: Unfolding

Two dimensional unfolding

Extend the method for LHCf-Arm2 analysis

- Strategy
    - Two dimensional unfolding using RooUnfold package
        - Iterative baysan method
    - Extend the method for LHCf-Arm2 analysis
        - LHCf-Arm2 analysis : https://doi.org/10.1007/JHEP11(2018)073
    - Two dimensional histograms for inputs/outputs
        - E_{rec} and N_{track} for input / E_{true} and N_{charged} for output
    - Response matrix
        - 1D response from ATLAS full simulation & 1D response from LHCf full simulation
            - Assumption : detector response of ATLAS and LHCf detector are independent
- Update
    - Performance test of unfolding
    - Systematic uncertainty
    - Candidate of final plots
- Remaining works
    - Systematic uncertainty due to unfolding

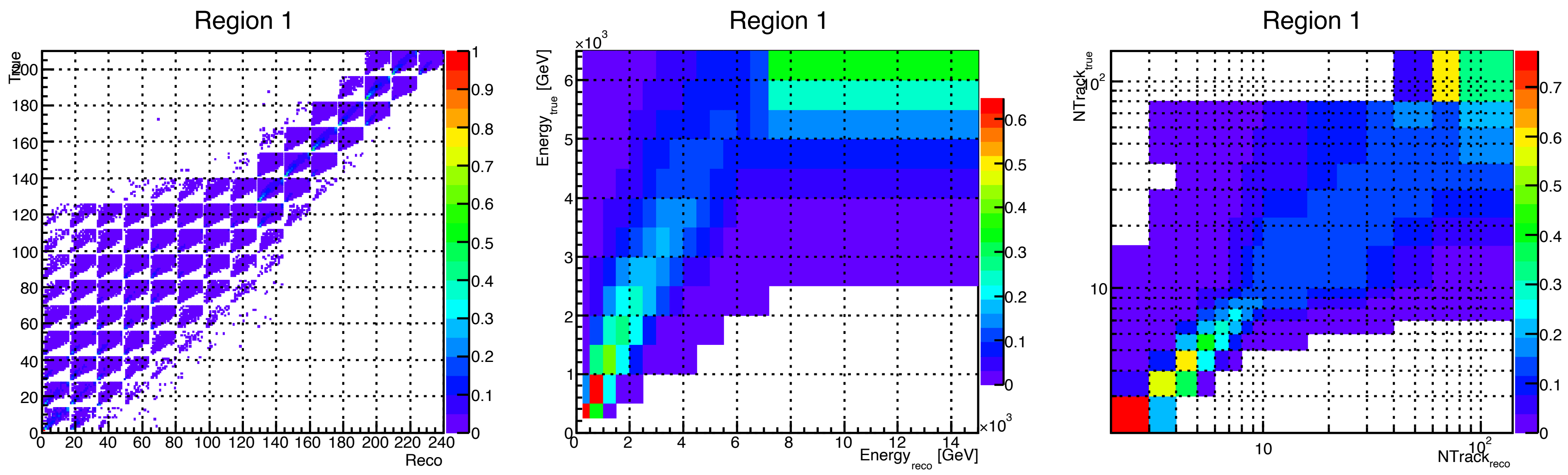
Response matrix



MC sample

ATLAS full simulation / LHCf full simulation

Response Matrix



Update from the last report :

Performance test of the unfolding method using the ATLAS-LHCf full MC. Then, the systematic uncertainty was estimated.

Unfolded spectrum

Two dimensional unfolded spectrum

Projection to each axis
Ratio of spectrum after projection

Unfolding performance test

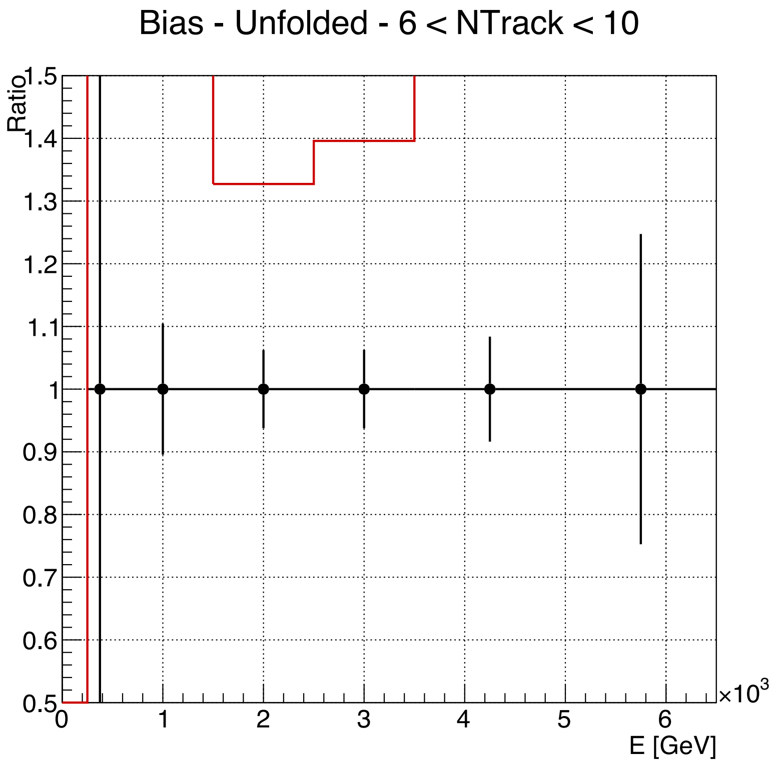
Full simulation
ATLAS + LHCf
PYTHIA8

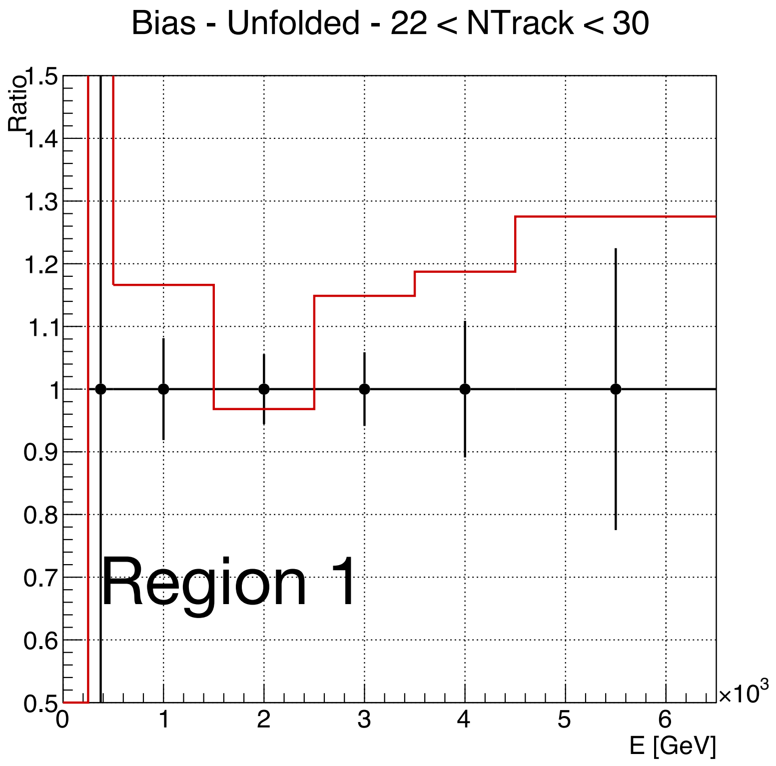
Truth correction → Folded spectrum

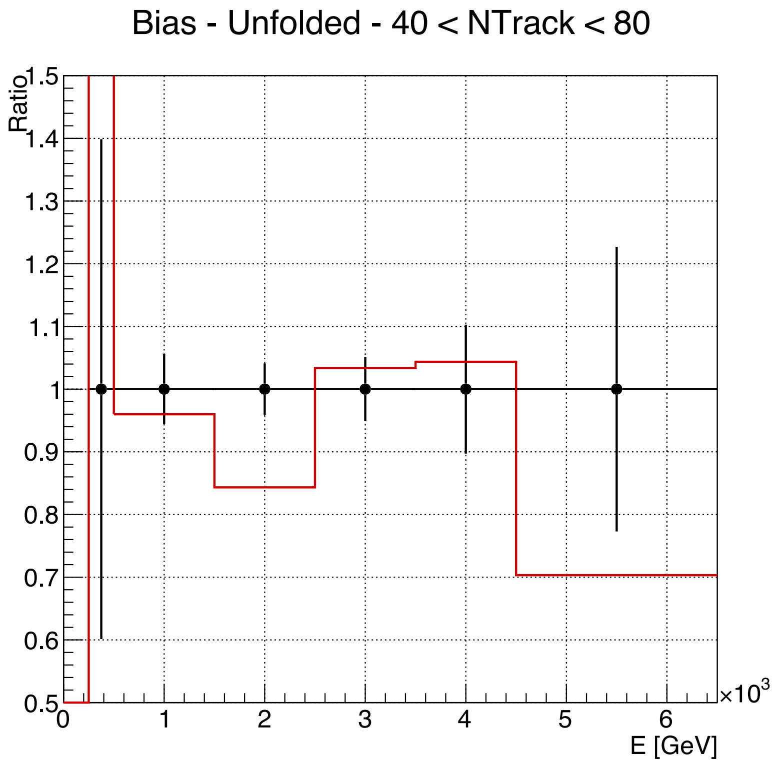
Unfolding → Unfolded spectrum

↘ True Spectrum

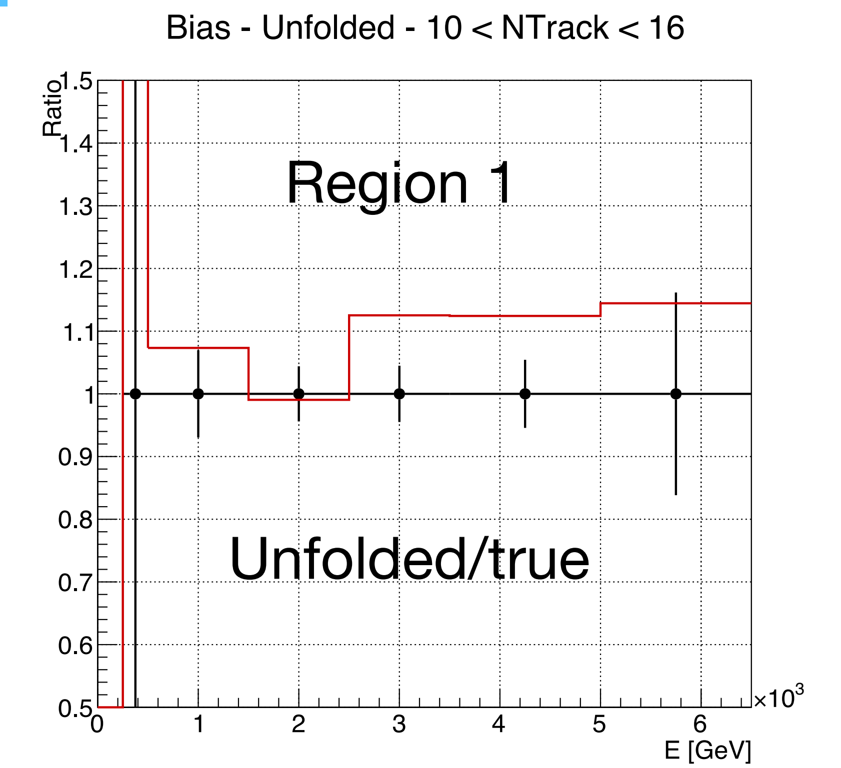
Ratio = (True spectrum)/(Unfolded spectrum)

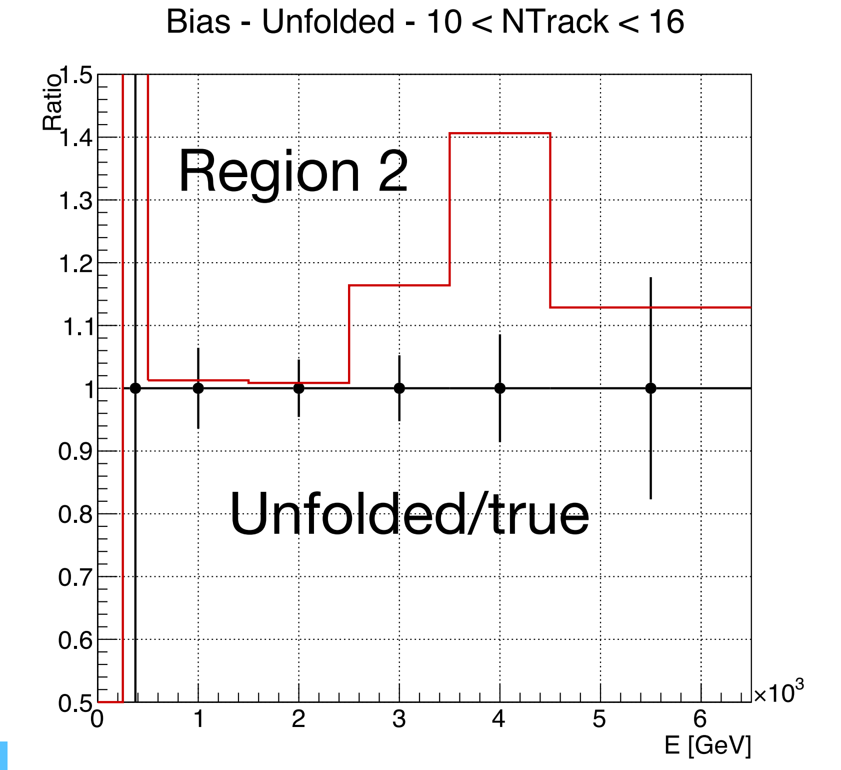






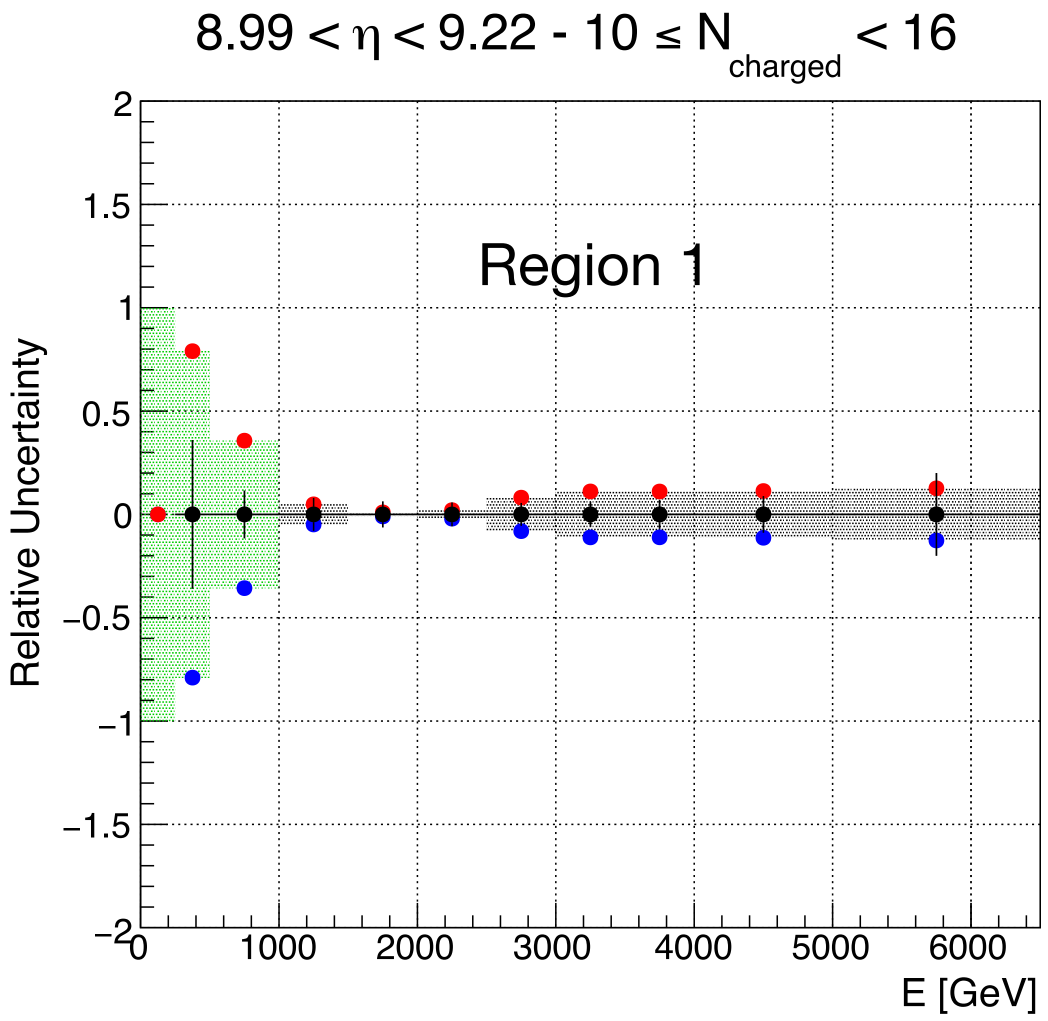
Systematic uncertainty

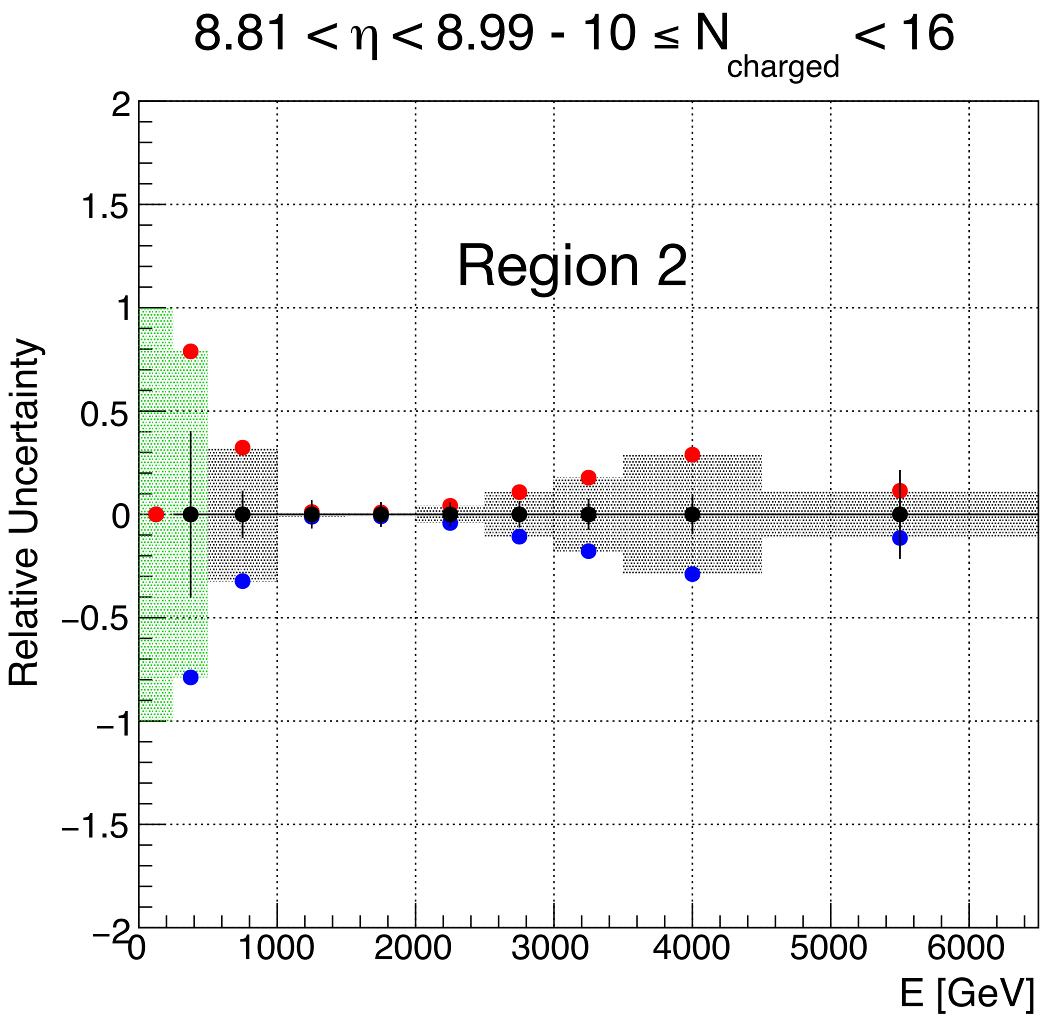




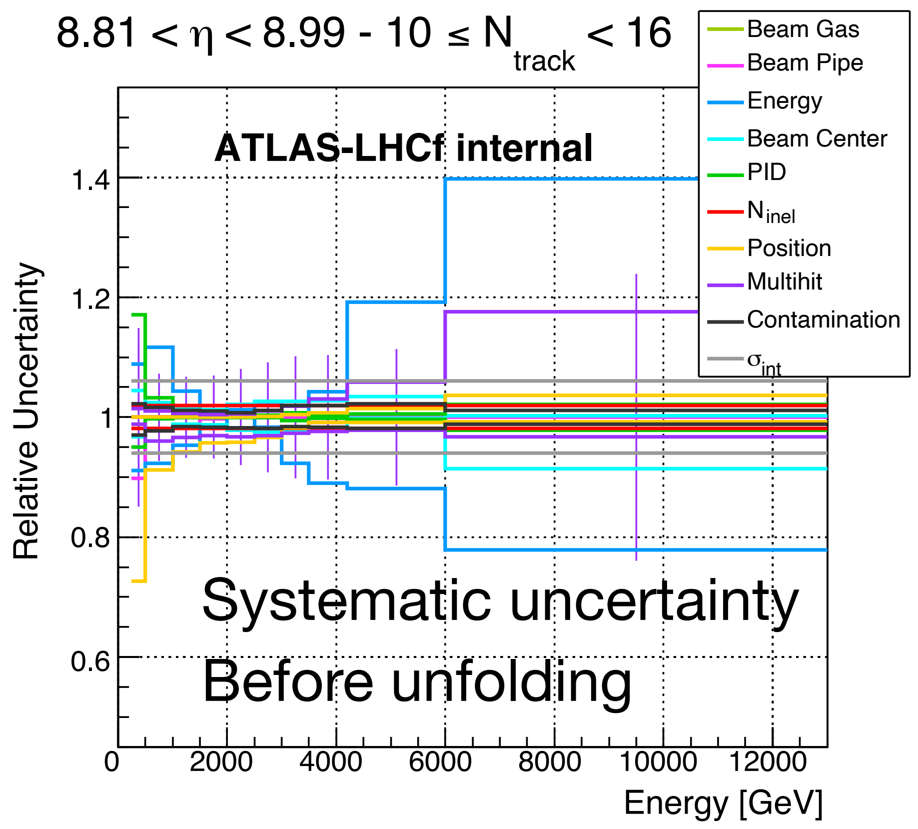
Uncertainty = true/unfolded

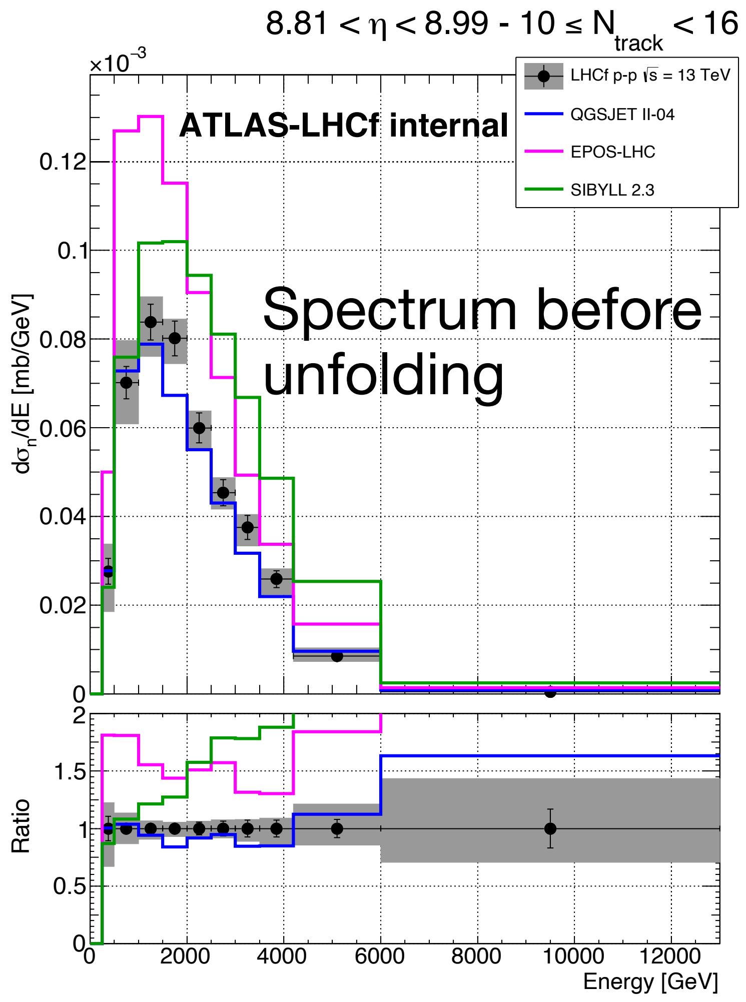
The size of uncertainty was used both upper and lower limits of uncertainty.

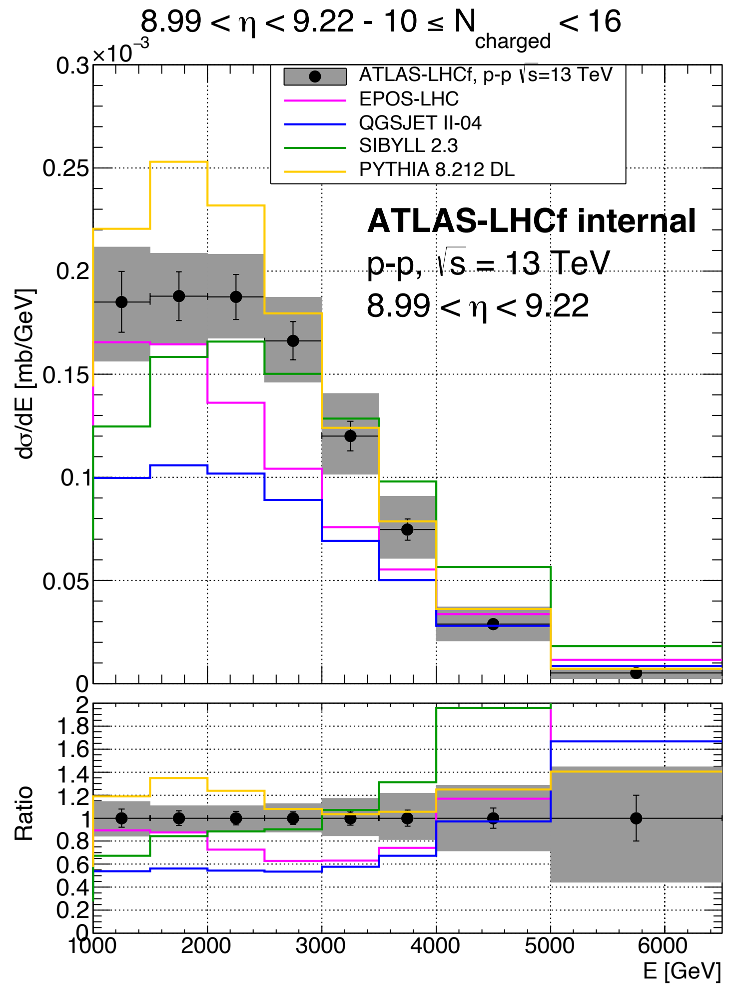




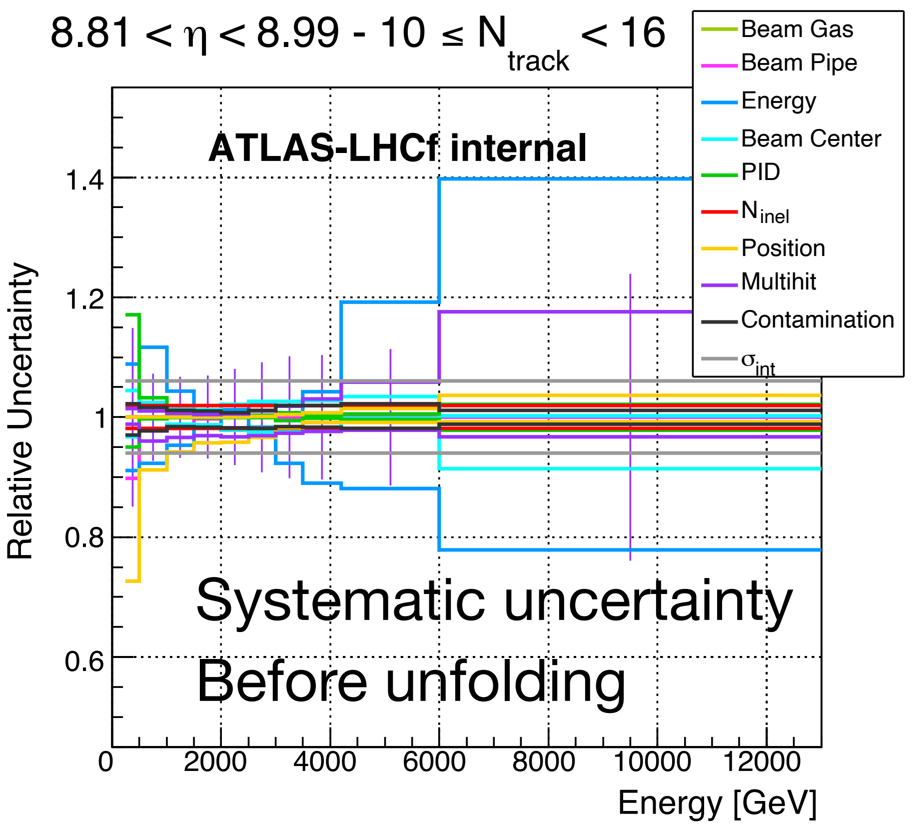
Unfolded result

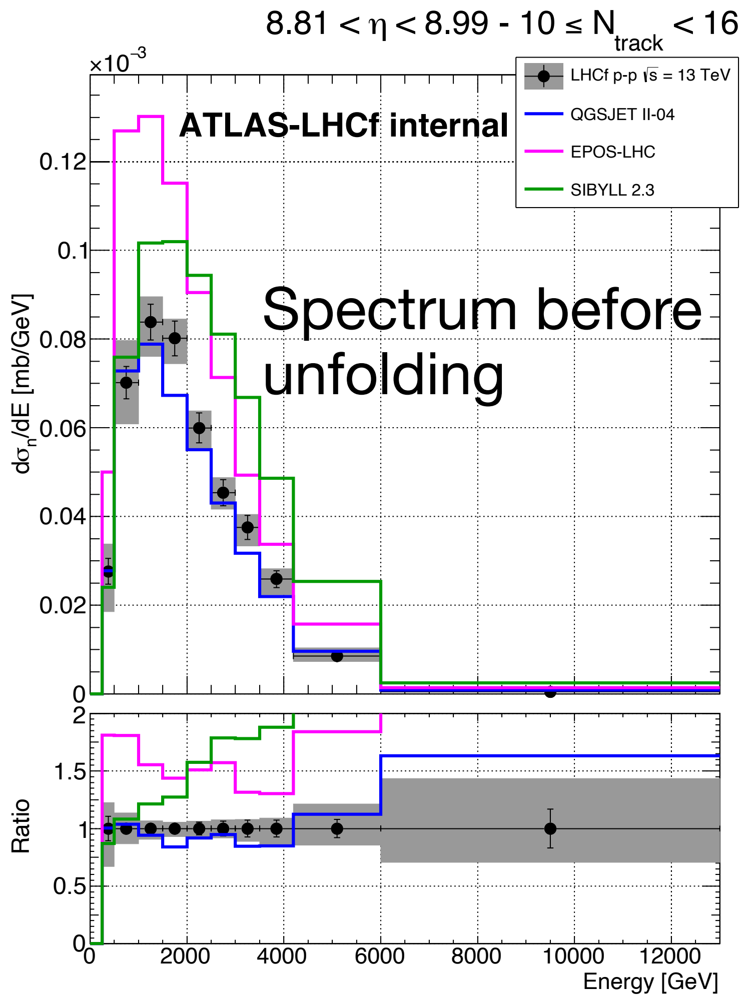






Propagation of systematic uncertainty

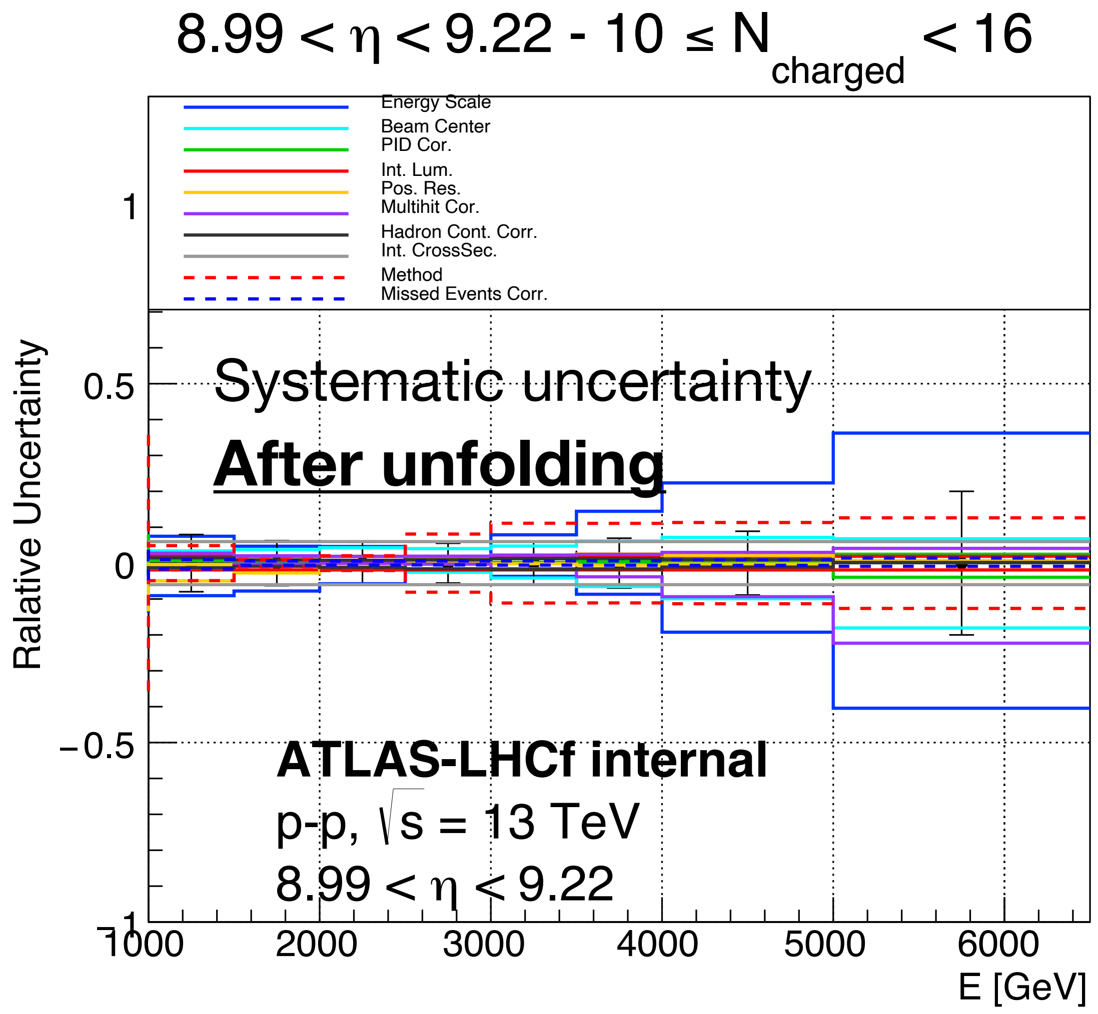




Calculations

Shift spectrum before unfolding using systematic uncertainty

Differences after unfolding were considered as uncertainty after unfolding



Missing points and updates after February

Validation of analysis procedure

There is a problem…… all spectra shows a factor 6/10 difference.

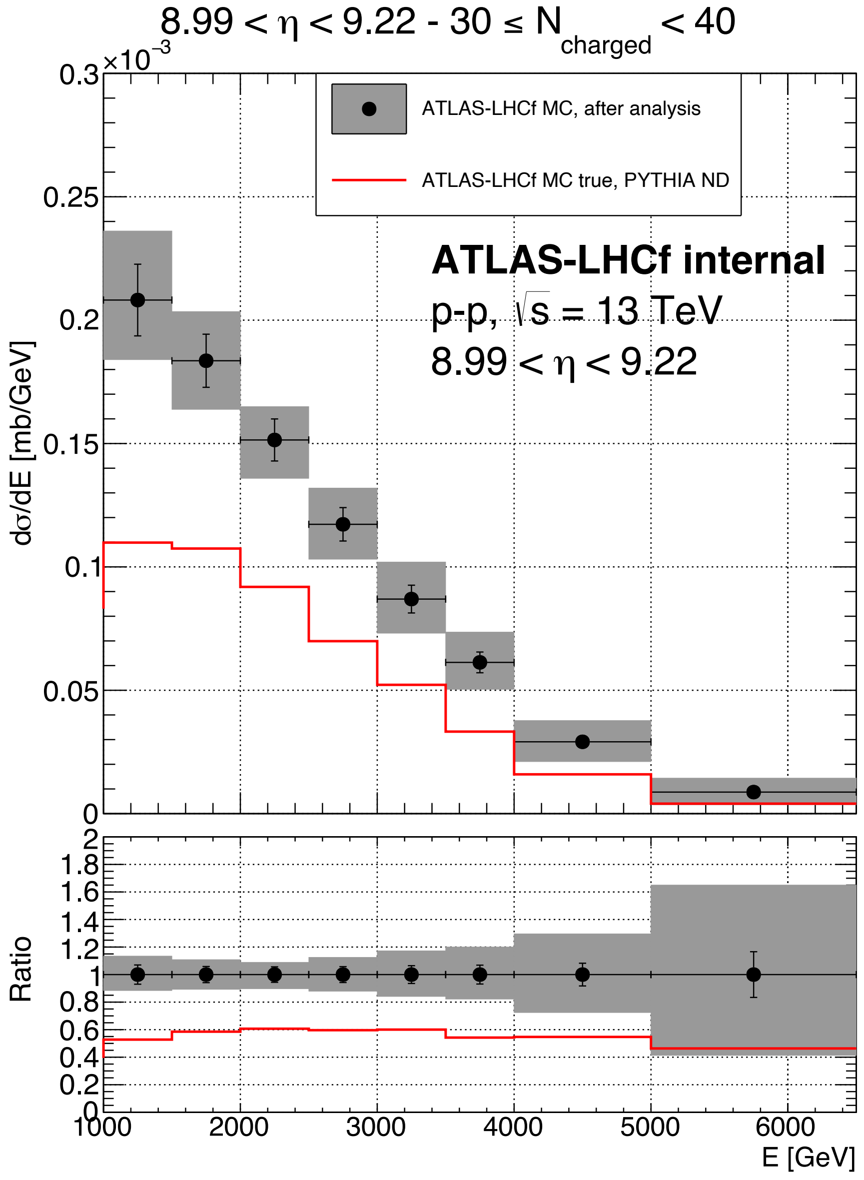
Full simulation
ATLAS + LHCf
PYTHIA8

All correction → Folded spectrum

↓ Unfolding

True Spectrum
Red line

Unfolded spectrum
Black points

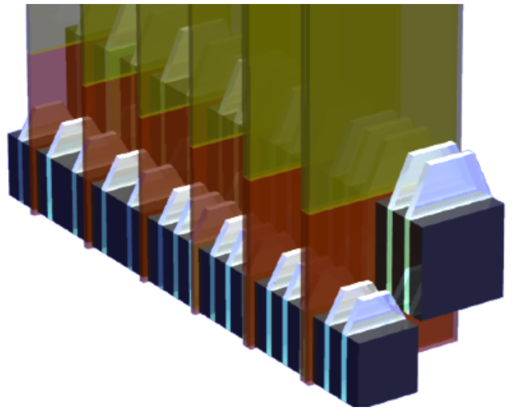


I used the same code for the data.
Maybe, there is a bug in my code……

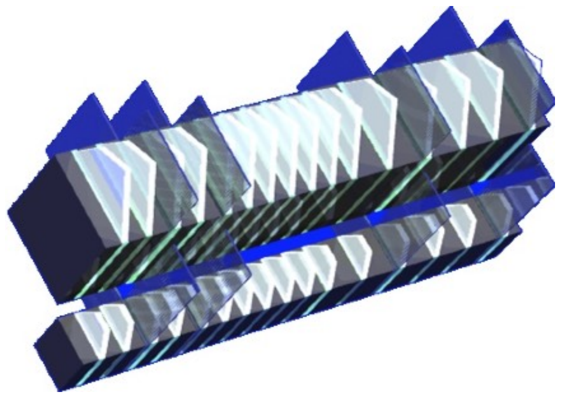
Detection efficiency (analyzed by Eugenio)

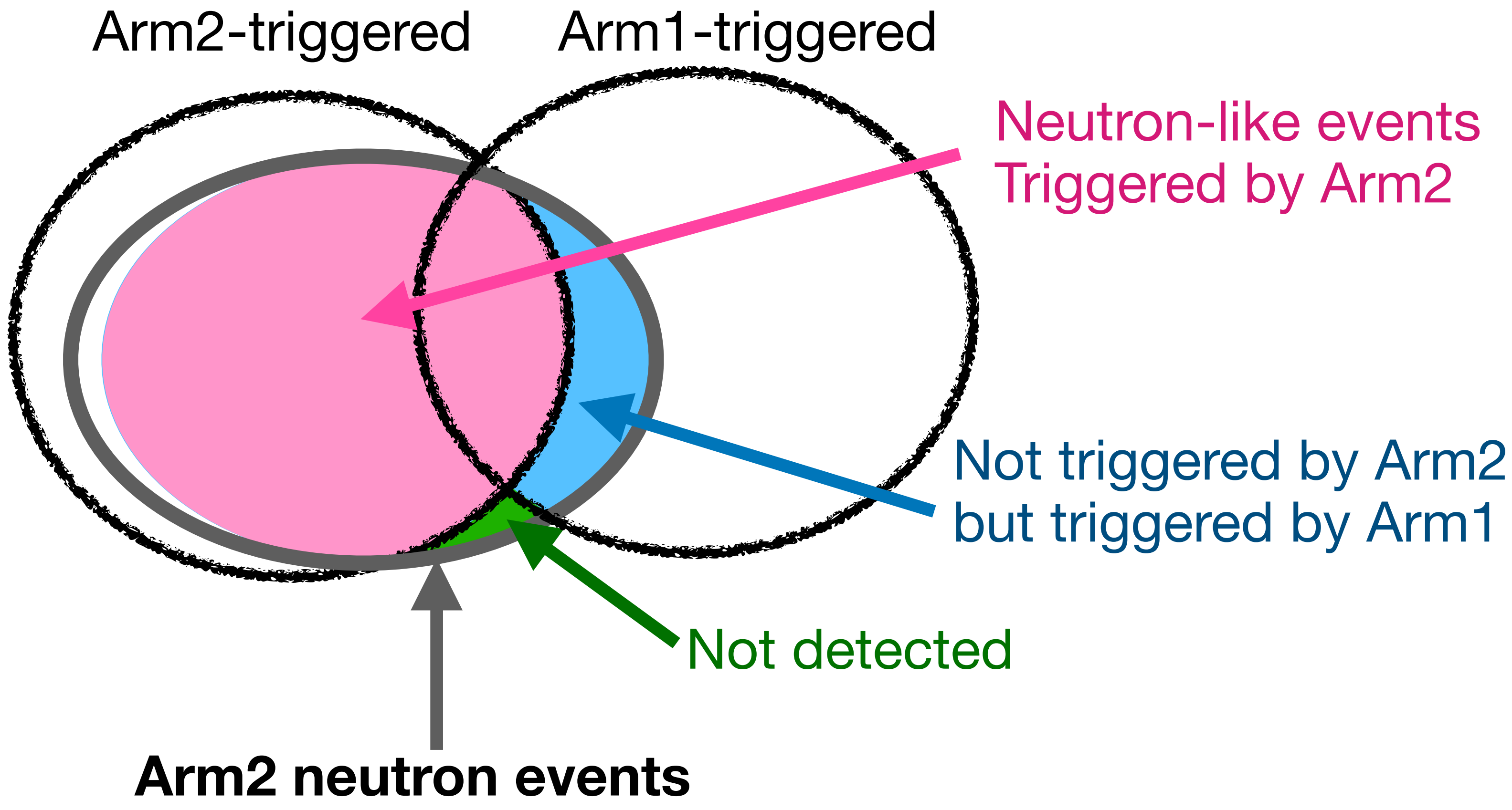
Data-driven validation of the trigger efficiency

LHCf Arm2 detector



LHCf Arm1 detector





<u>Dataset: events triggered by the Arm1 or Arm2 detector</u>

<u>Arm2 neutron-like events selection</u>

- Arm2 software trigger
- Position in the analysis regions
- $L_{2D} > L_{thres}$
- $E_{reco} > 250\,\mathrm{GeV}$

<u>Select neutron-like events in all data-set</u>

Detection efficiency (analyzed by Eugenio)

Data-driven validation of the trigger efficiency

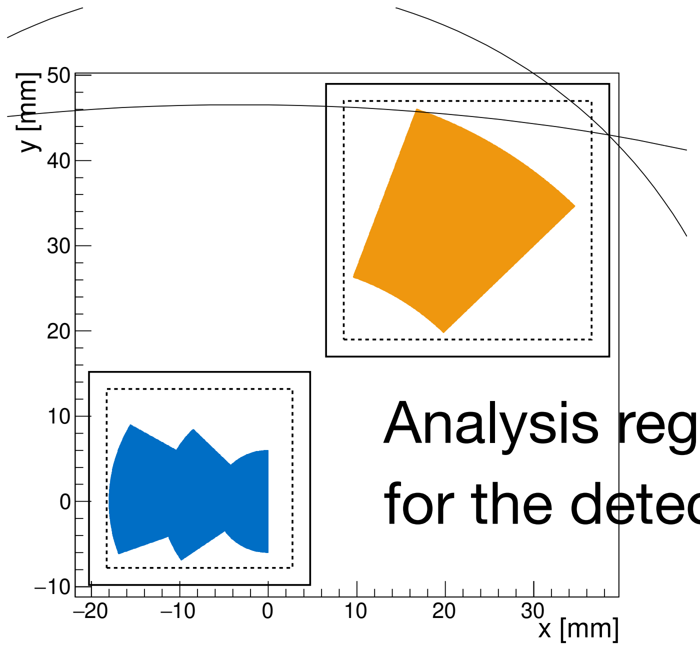
Dataset: events triggered by the Arm1 or Arm2 detector

$\epsilon = N_{\text{triggered}} / N^{\text{data-set}}_{\text{neutron-like}}$

Arm2 neutron-like events selection $N_{\text{triggered}}$

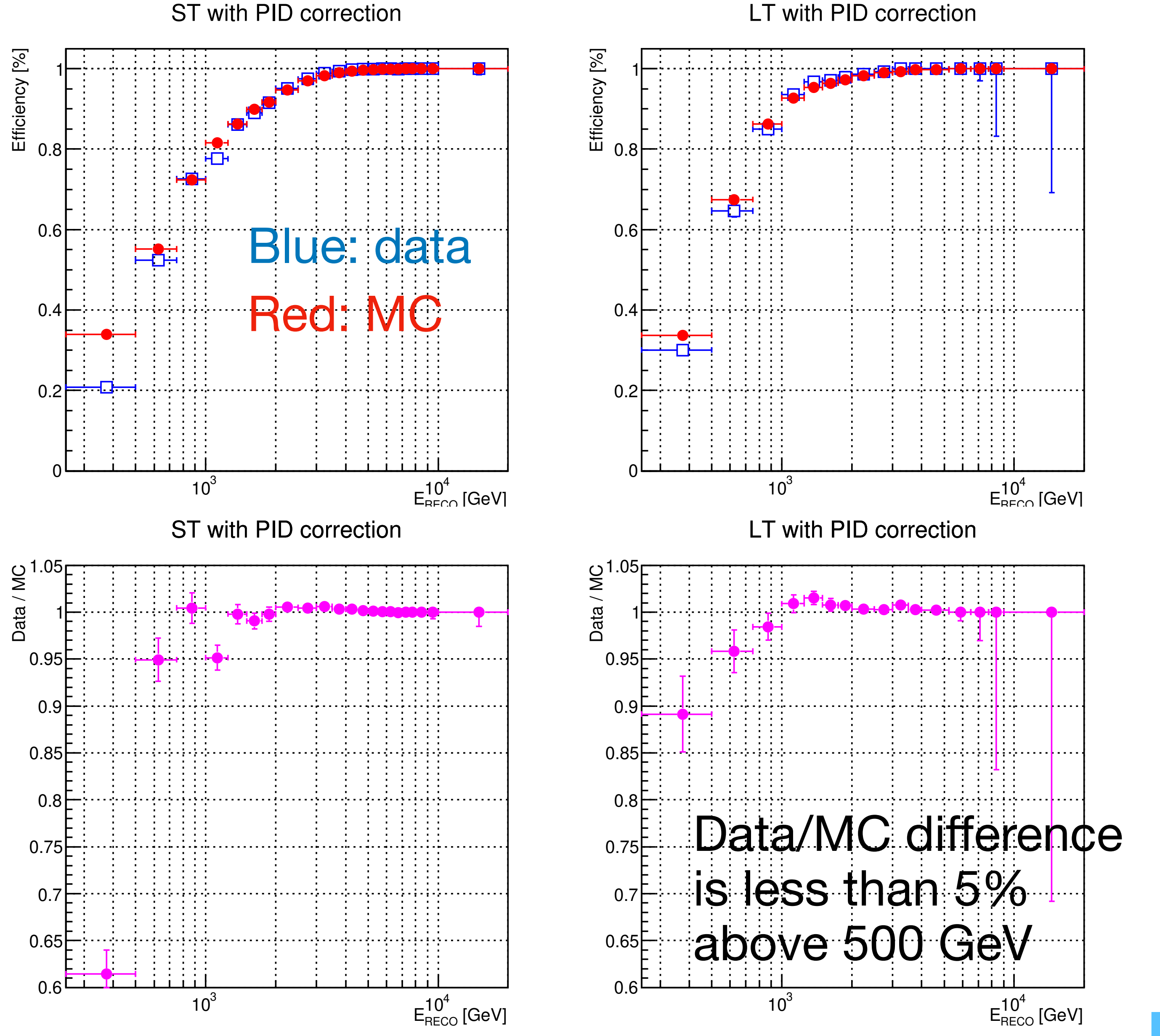
- Arm2 software trigger
- Position in the analysis regions
- $L_{2D} > L_{\text{thres}}$
- $E_{\text{reco}} > 250\,\text{GeV}$

Select neutron-like events in all data-set $N^{\text{data-set}}_{\text{neutron-like}}$



Analysis region for the detection efficiency

I will add this correction later.



Summary

- There is a clear difference in the central-forward correlations between hadronic interaction models due to the modeling of the multi-parton interactions.
  - By measuring the very forward neutron productions as a function of the number of charged particles in the central detectors, we can constrain this modeling
- Most parts of the analysis were finished and the internal note was mostly filled.
  - The multi-hit correction was a major issue of this analysis for a few years, but finally, we found a good method to estimate it.
  - Detection efficiency was a major comment given in the last ATLAS soft QCD meeting. It was calculated by Eugenio.
- But I have several remaining parts
  - Unknown factor differences in the procedure validation.
  - Add the detection efficiency correction.
  - The binning of the number of charged particles, especially $N_{\mathrm{charged}} < 10$, has to be finalized since it was asked in the last ATLAS soft QCD meeting.
  - Finalize the internal note

Back-up

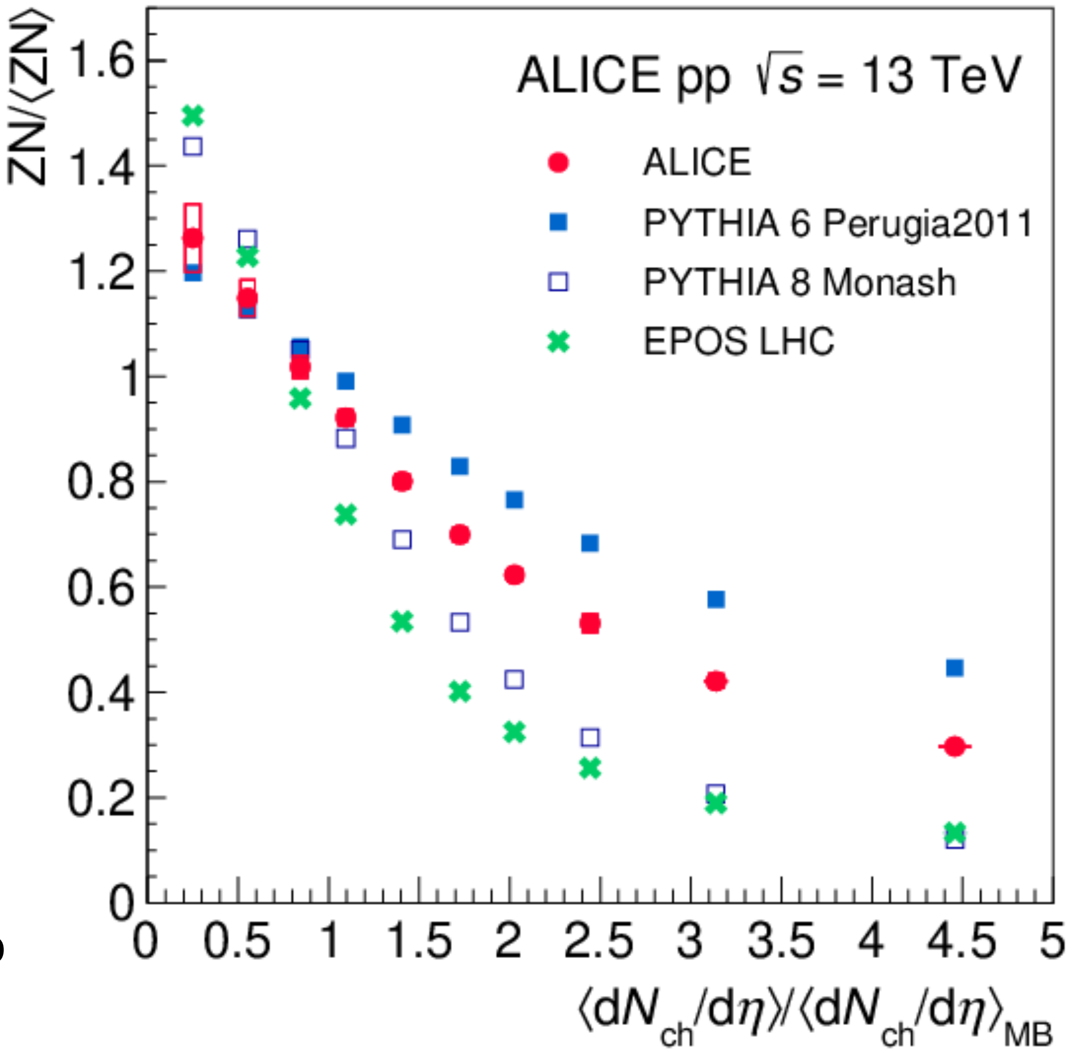
Recent paper by ALICE-ZDC

Similar study was performed by ALICE-ZDC (arXiv : arXiv:2107.10757)

- Using ALICE-ZDC, they show correlation between multiplicity in $|\eta| < 1$ and forward signals.
  - Neutron modules of the ALICE-ZDC cover $|\eta| > 8.8.$
    - Proton modules cover $6.5 < |\eta| < 7.4.$
  - They do not convert signals to energy, but normalize signals by the mean of signals with minimum-bias measurements.
  - Differences between models are caused by MPI mechanism.
- Advantage of ATLAS-LHCf measurements
  - We can measure forward neutron energy, so we can compare energy spectrum with selections by multiplicity.

ALICE results, arXiv:2107.10757 / CERN-EP-2021-144

Ratio of ZDC signals to mean of ZDC signals in minimum-bias measurements



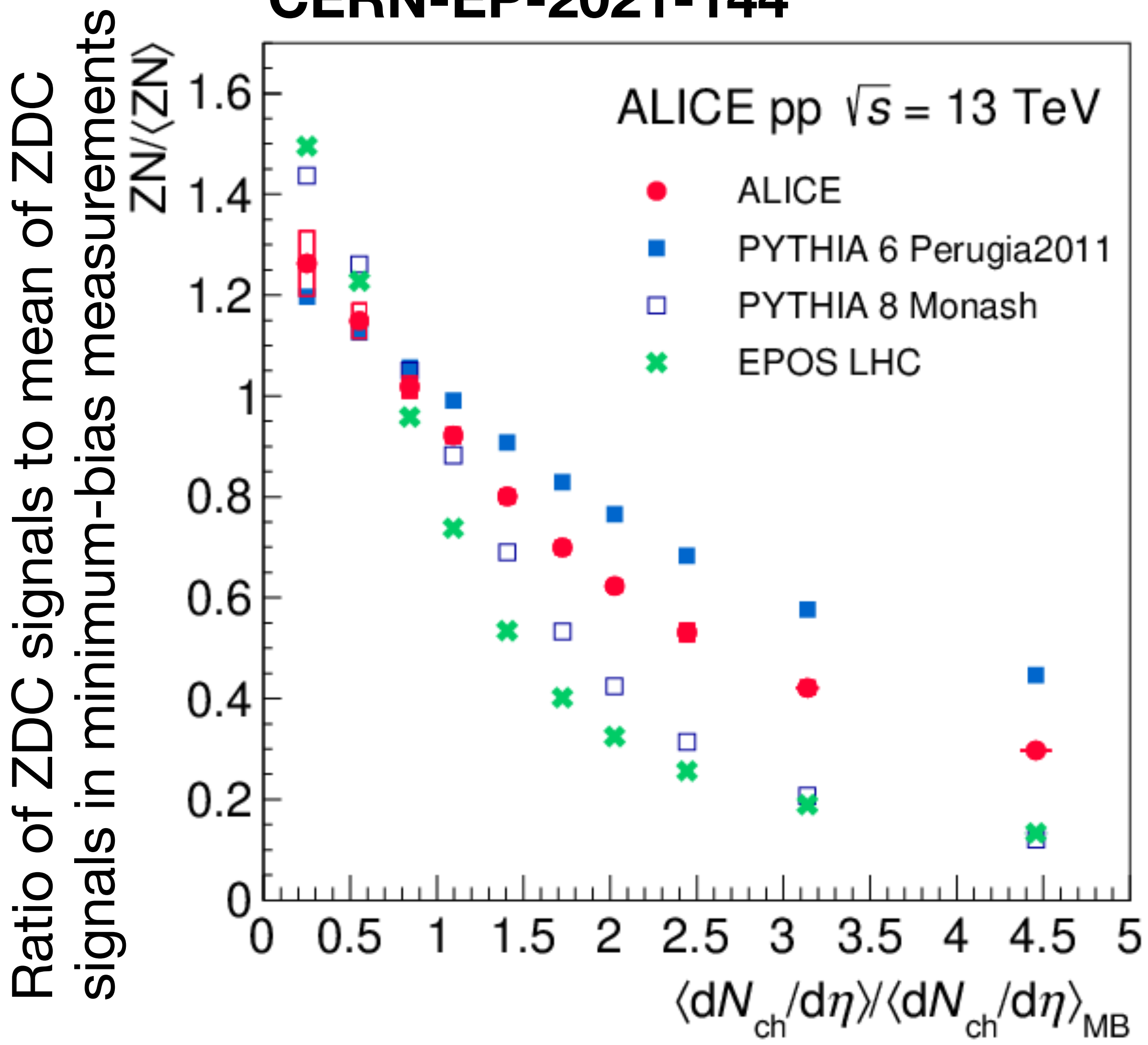
Ratio of mean of the number of charged particles to minimum-bias measurements

Recent paper by ALICE-ZDC

Similar study was performed by ALICE-ZDC (arXiv : arXiv:2107.10757)

- Using ALICE-ZDC, they show correlation between multiplicity in $|\eta| < 1$ and forward signals.
    - Neutron modules of the ALICE-ZDC cover $|\eta| > 8.8$.
        - Proton modules cover $6.5 < |\eta| < 7.4$.
    - They do not convert signals to energy, but normalize signals by the mean of signals with minimum-bias measurements.
    - Differences between models are caused by MPI mechanism.
- Advantage of ATLAS-LHCf measurements
    - We can measure forward neutron energy, so we can compare energy spectrum with selections by multiplicity.

ALICE results, arXiv:2107.10757 / CERN-EP-2021-144

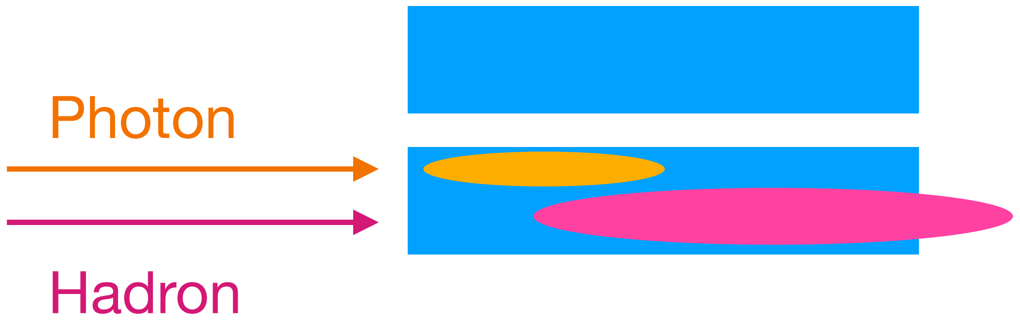


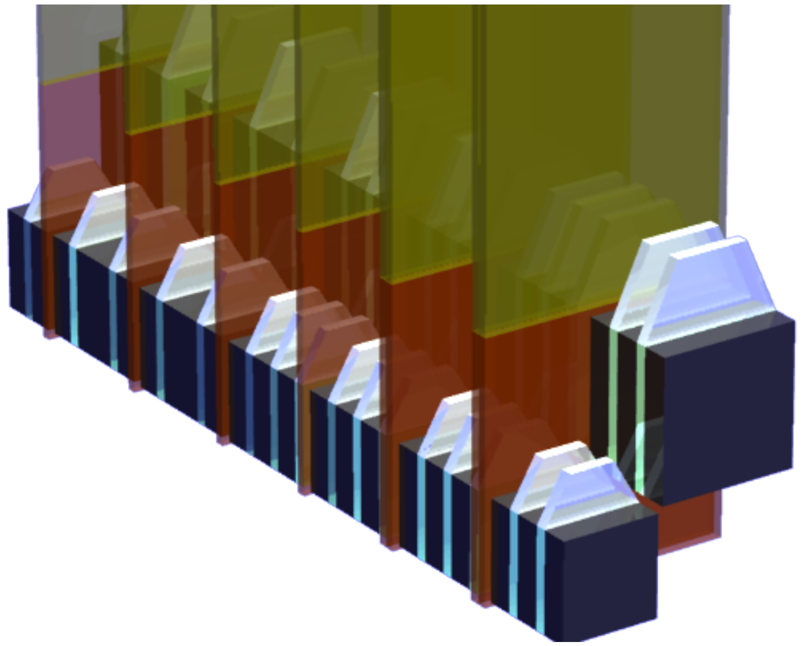
Ratio of mean of the number of charged particles to minimum-bias measurements

Validation and tuning of multi-hit predictions

Using first 6 layers as veto of multi-hit events

- In multihit events with photon and hadron in a tower,
  - An electromagnetic shower develops in early parts of the calorimeter tower.
  - A hadronic shower develops in later parts of the calorimeter shower.
  - So most of h + γ multihit events, energy deposits in early layers are expected.
- Idea
  - Make multi-hit reduced/enhanced samples using energy deposits in early layers.
  - Then, validate MC predictions from comparison of energy spectra of these samples.





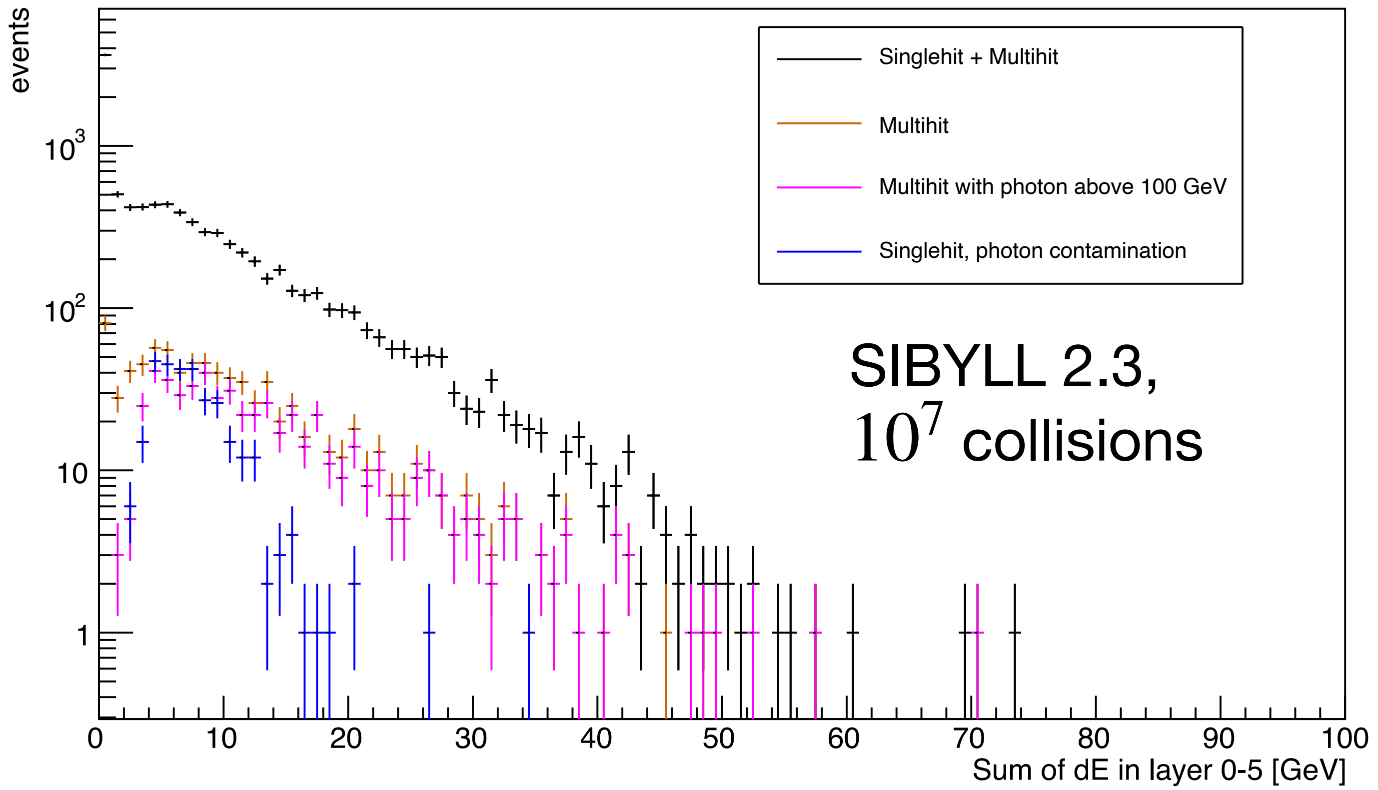
Position sensitive layers before layer 2/5/8
=> energy deposits in layer 2,5,8 were affected.
(Larger gaps between tungsten and scintillator.)

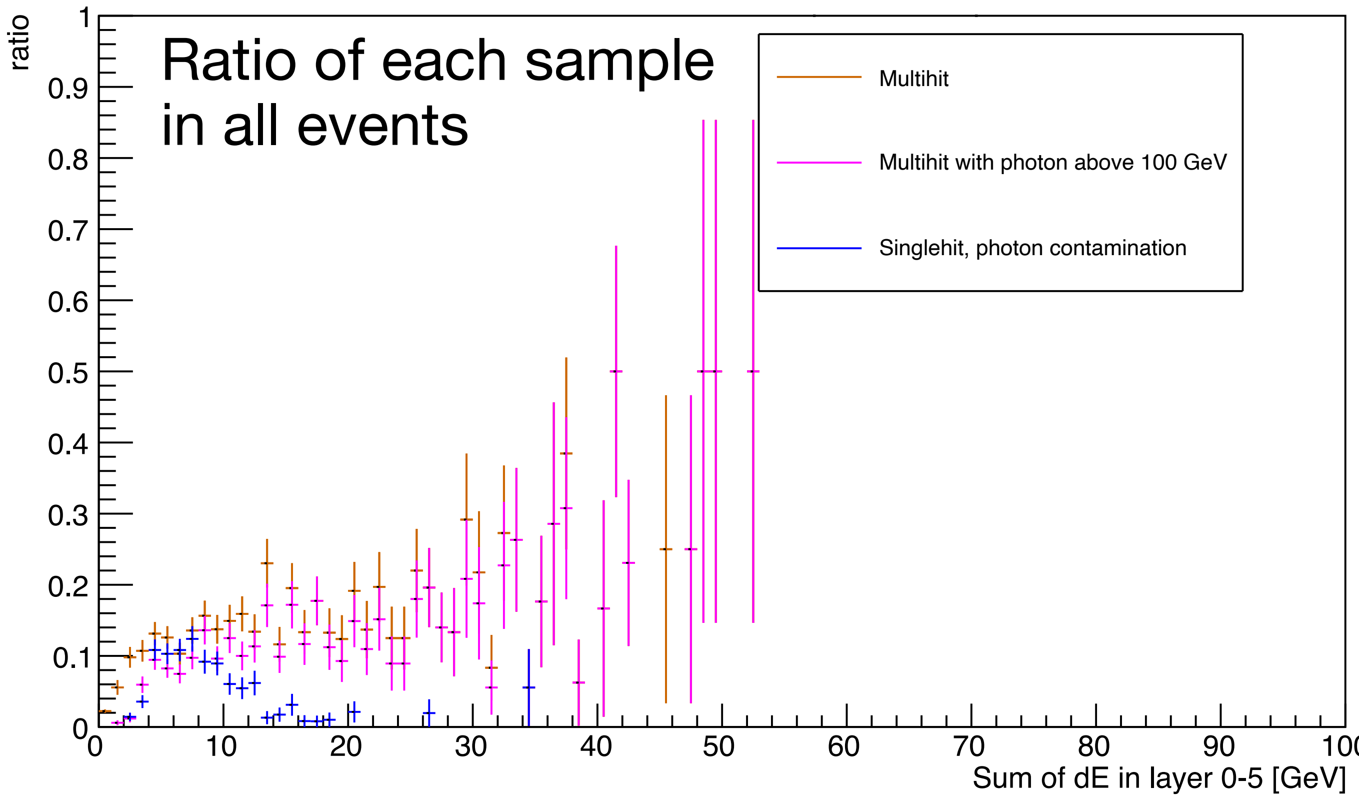
Multi-hit enhanced/reduced samples

Sum of energy deposits in layer 0-5

Large tower, Region 1 (by reconstructed positions),

$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger





Black : all events

Orange : multi-hit in true level

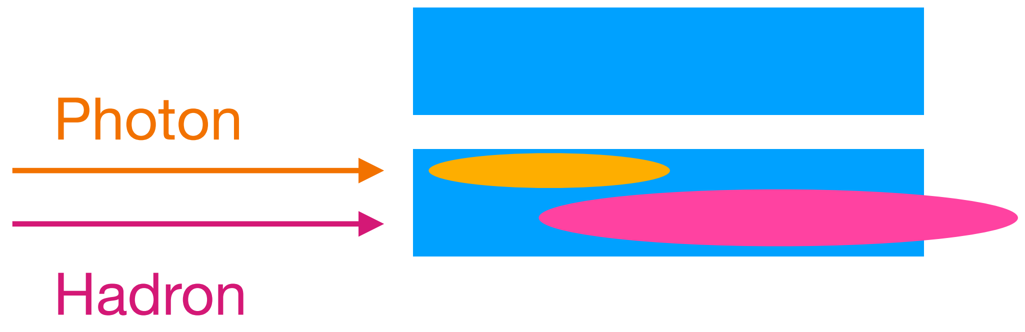
Magenta : multi-hit, h + γ, $E_{true} > 100$ GeV for each

Blue : single-hit photon (contamination)

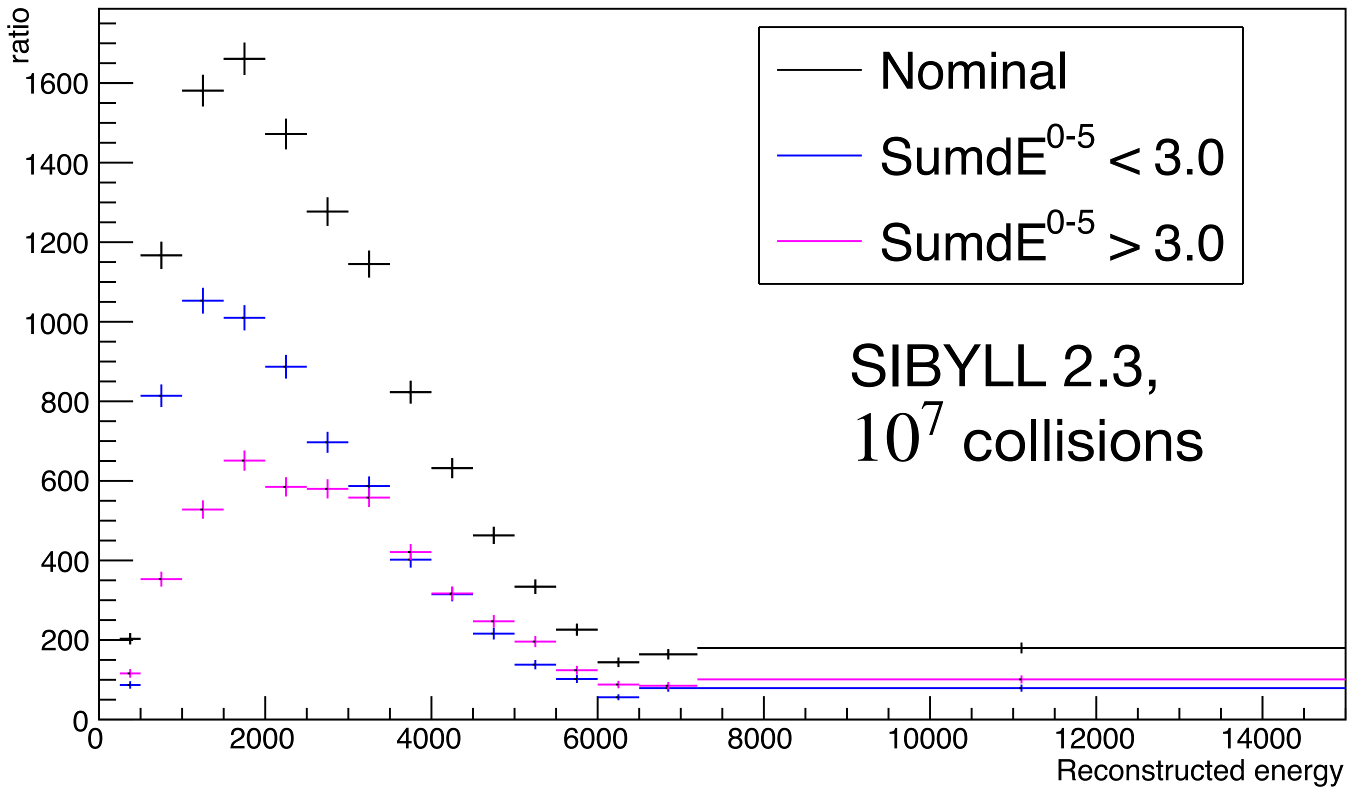
We can select the multi-hit reduced sample by selecting small energy deposits in the first 6 layers.

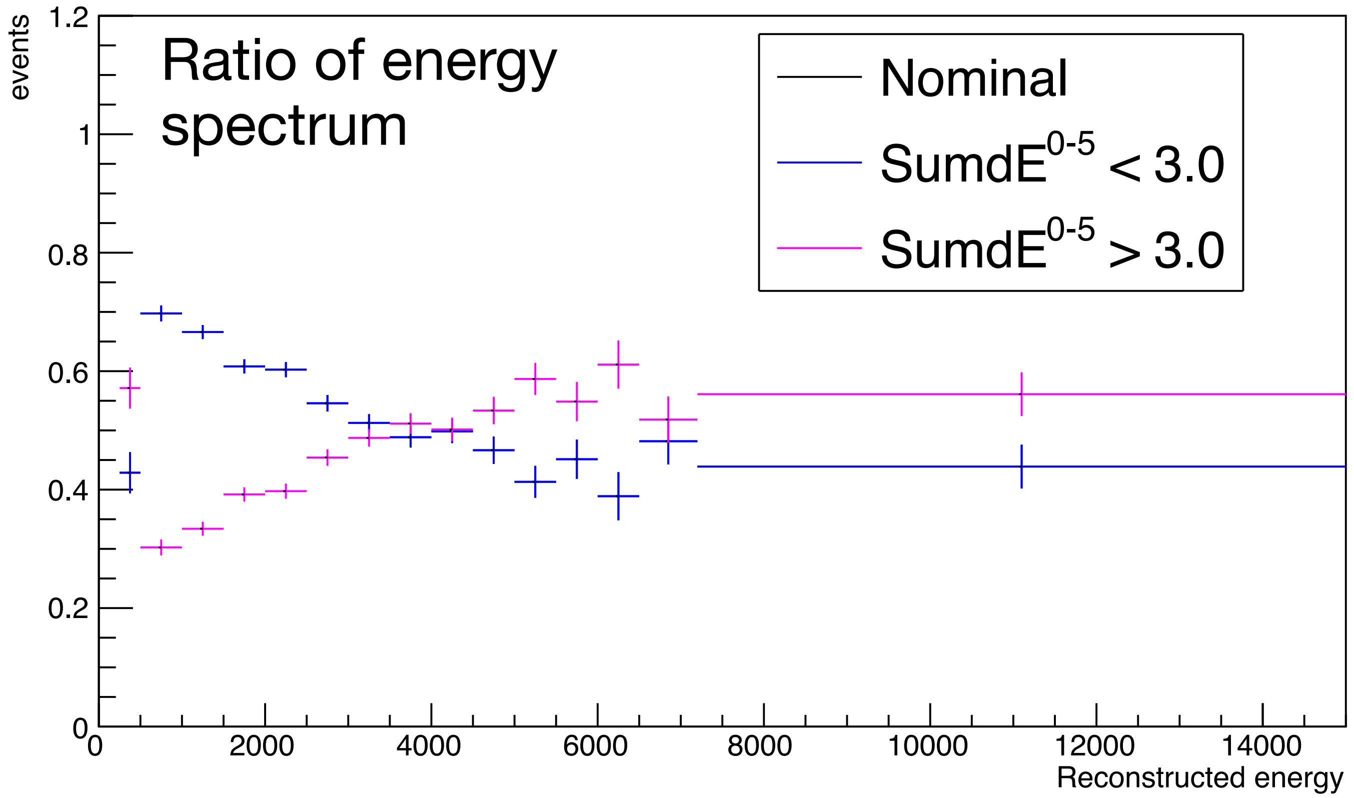
Energy spectrum

Multi-hit reduced / enhanced samples



Large tower, Region 1 (by reconstructed positions),
$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger



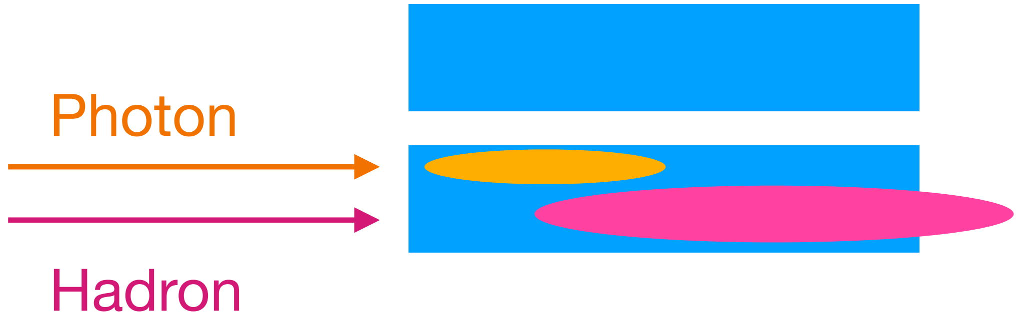


Black : all events
Blue : small energy deposits (Multi-hit reduced sample)
Magenta : large energy deposits (Multi-hit enhanced sample)

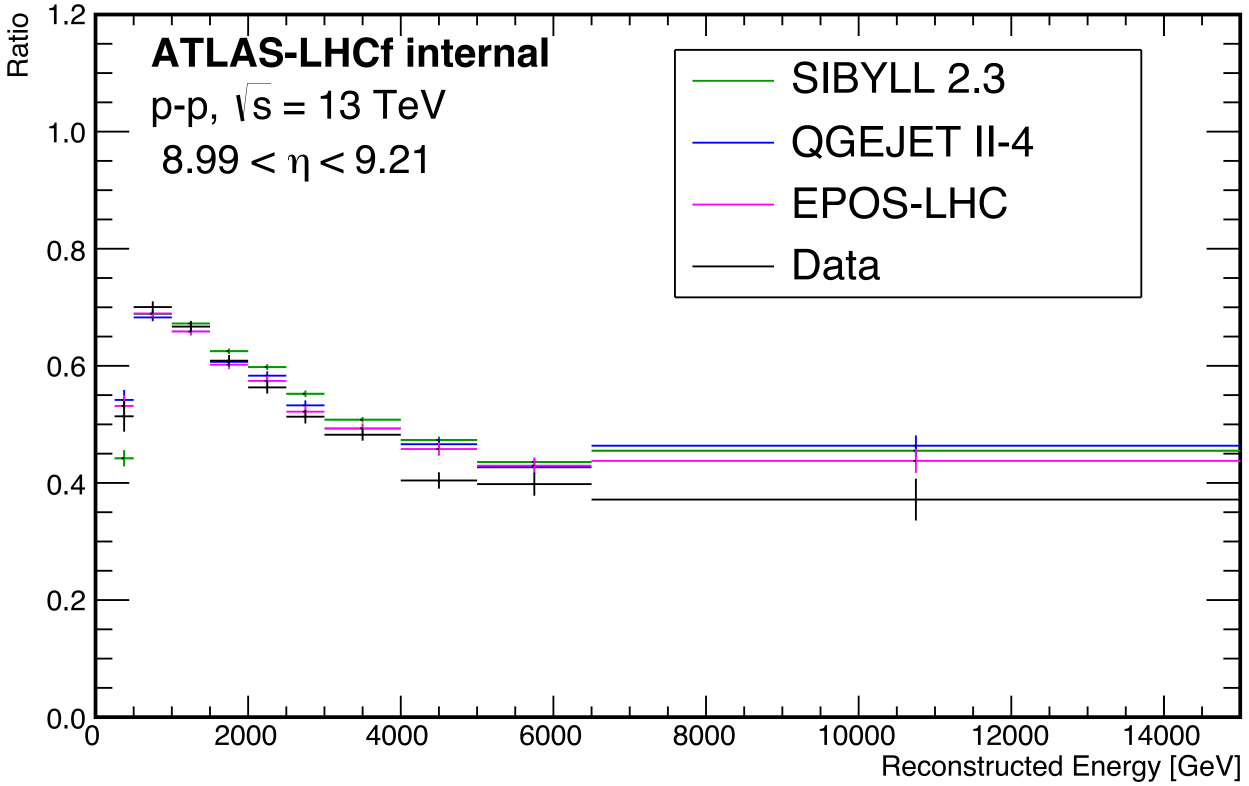
Possibility of validation!!

Ratio of energy spectrum

Ratio = (multi-hit reduced)/(nominal spectrum)



Large tower, Region 1 (by reconstructed positions),
$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger



We found differences between data and MC predictions.

=> Template fitting using two free parameters for the normalization of contamination and multi-hit events

Step 1) Get a multi-hit normalization factor γ for the multi-hit corrections using the template fitting.

Step 2) Apply the factor γ and its error to the multi-hit predictions and get modified multi-hit corrections and its error.

$$C^{\mathrm{MH}} = \frac{N^{\mathrm{MH\ ideal}} + N^{\mathrm{SH}}}{N^{\mathrm{MH\ obsreved}} + N^{\mathrm{SH}}}$$ (correction before tuning)

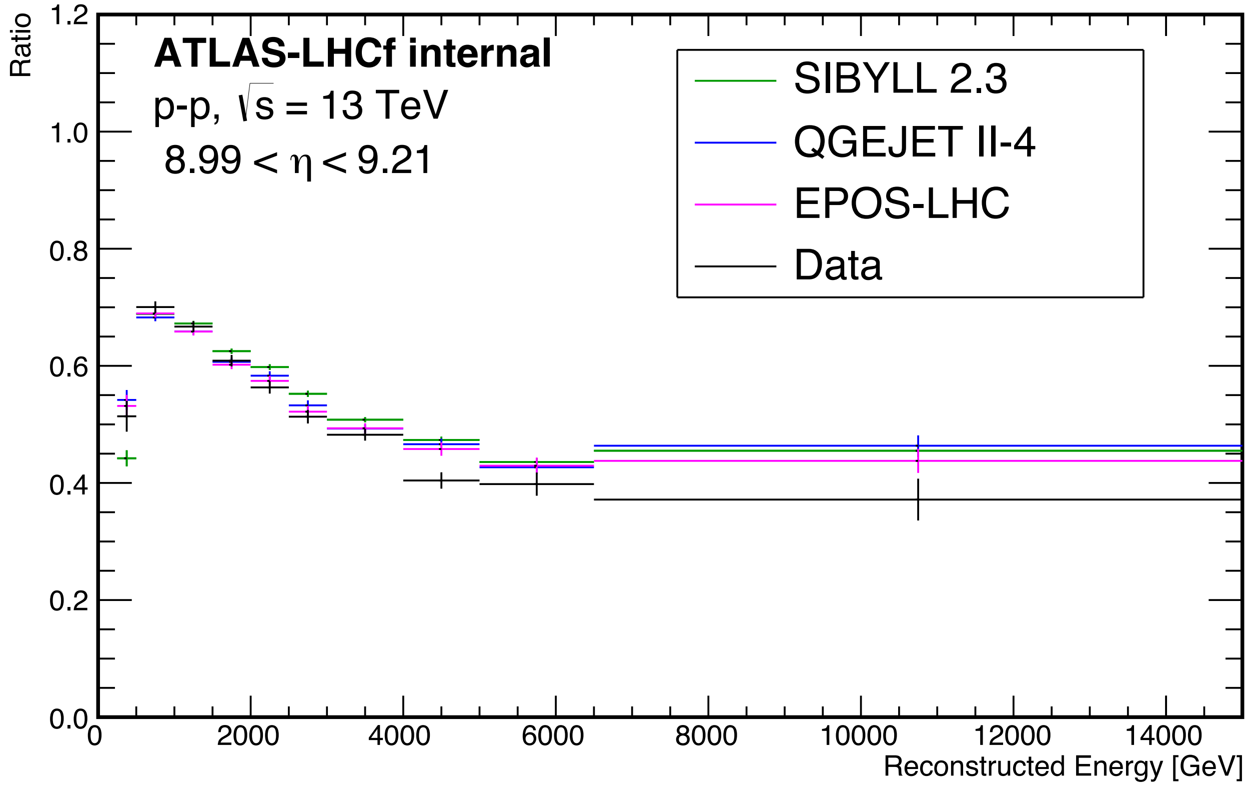
=> $$C^{\mathrm{MH}} = \frac{\gamma N^{\mathrm{MH\ ideal}} + N^{\mathrm{SH}}}{\gamma N^{\mathrm{MH\ obsreved}} + N^{\mathrm{SH}}}$$ (correction after tuning)

Template fitting

Ratio of multi-hit reduced to inclusive

Large tower, Region 1 (by reconstructed positions),

$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger



Minimizing the following value

$$\sum \frac{(R^{\mathrm{data}} - R^{\mathrm{MC}})^2}{\sigma^{R^{\mathrm{data}}} + \sigma^{R^{\mathrm{MC}}}}$$

$$R^{MC} = \frac{\alpha N_{\mathrm{cut}}^{\mathrm{single-photon}} + \beta N_{\mathrm{cut}}^{\mathrm{single-hadron}} + \gamma N_{\mathrm{cut}}^{\mathrm{multihit}}}{\alpha N^{\mathrm{single-photon}} + \beta N^{\mathrm{single-hadron}} + \gamma N^{\mathrm{multihit}}}$$

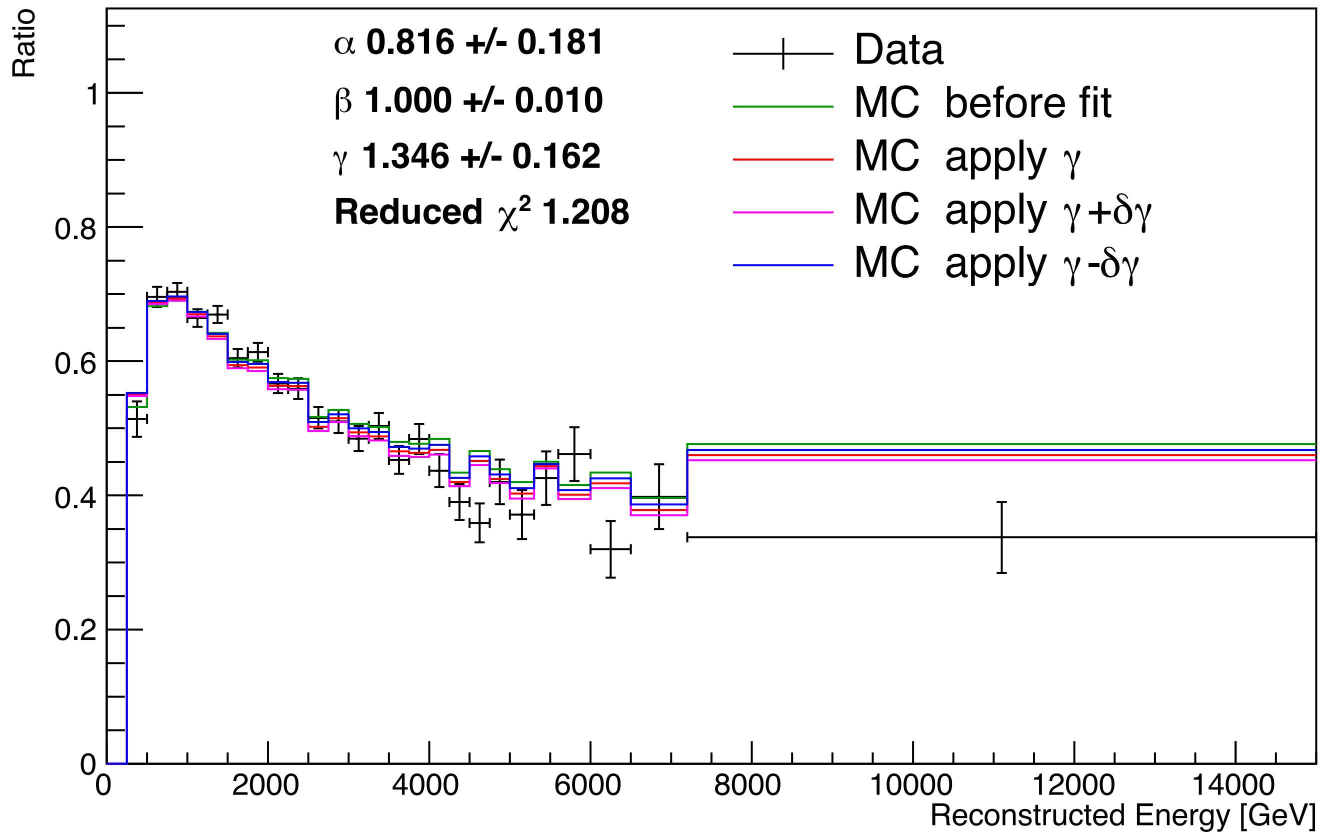
Parameter β is fixed to 1.0

Template fitting using EPOS-LHC

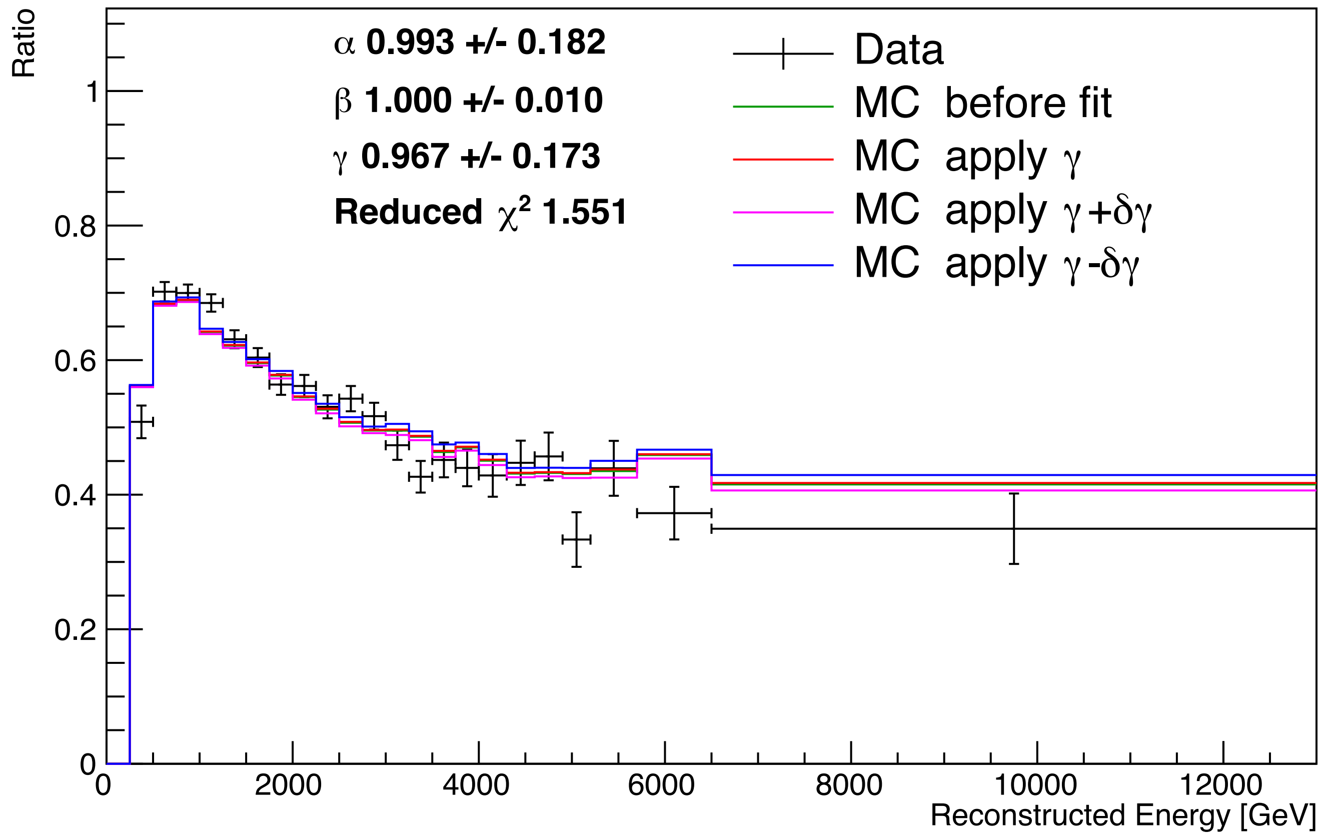
Ratio of multi-hit reduced to inclusive

Large tower, Region 1 and 2 (by reconstructed positions),
$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger

Region 1



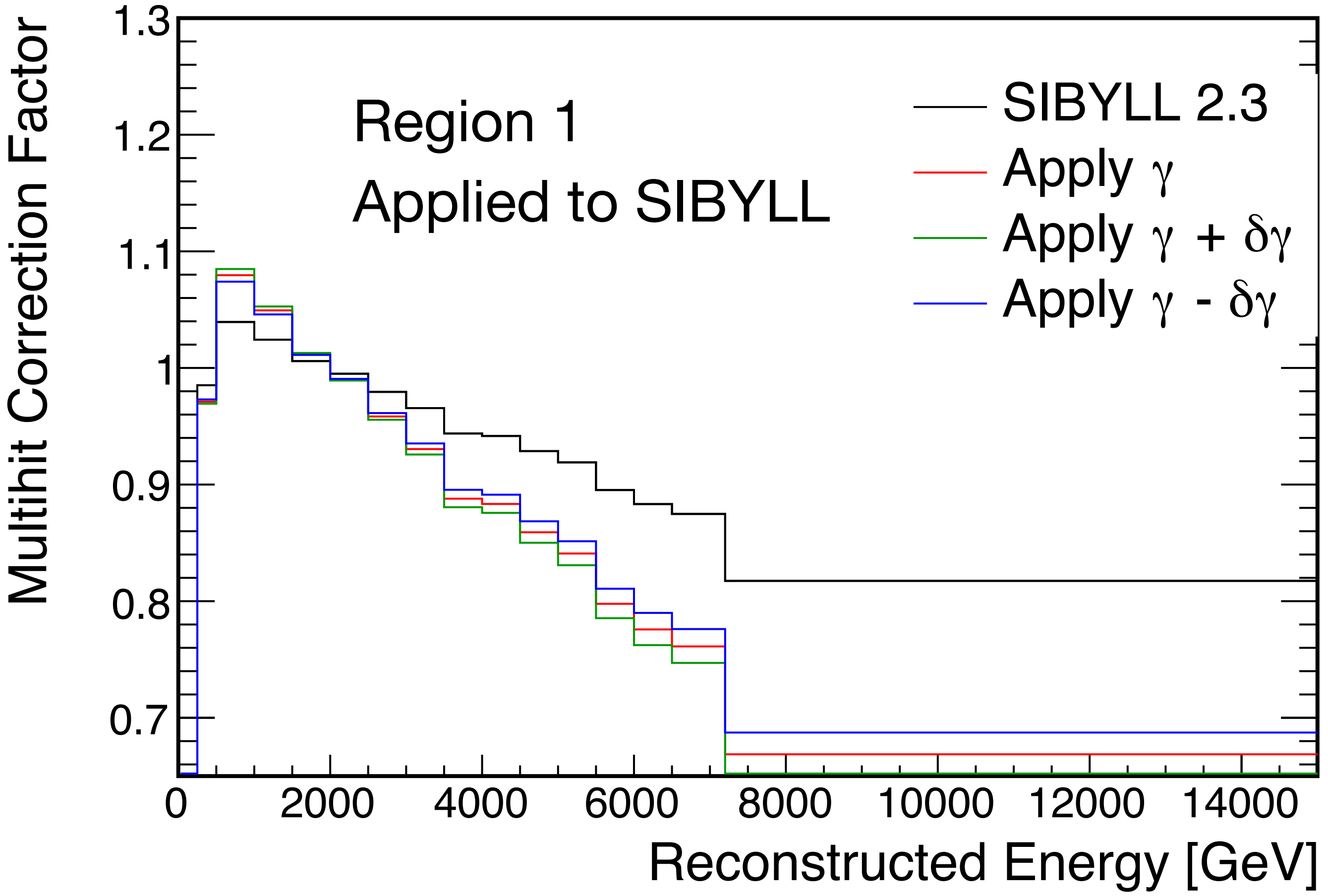
Region 2

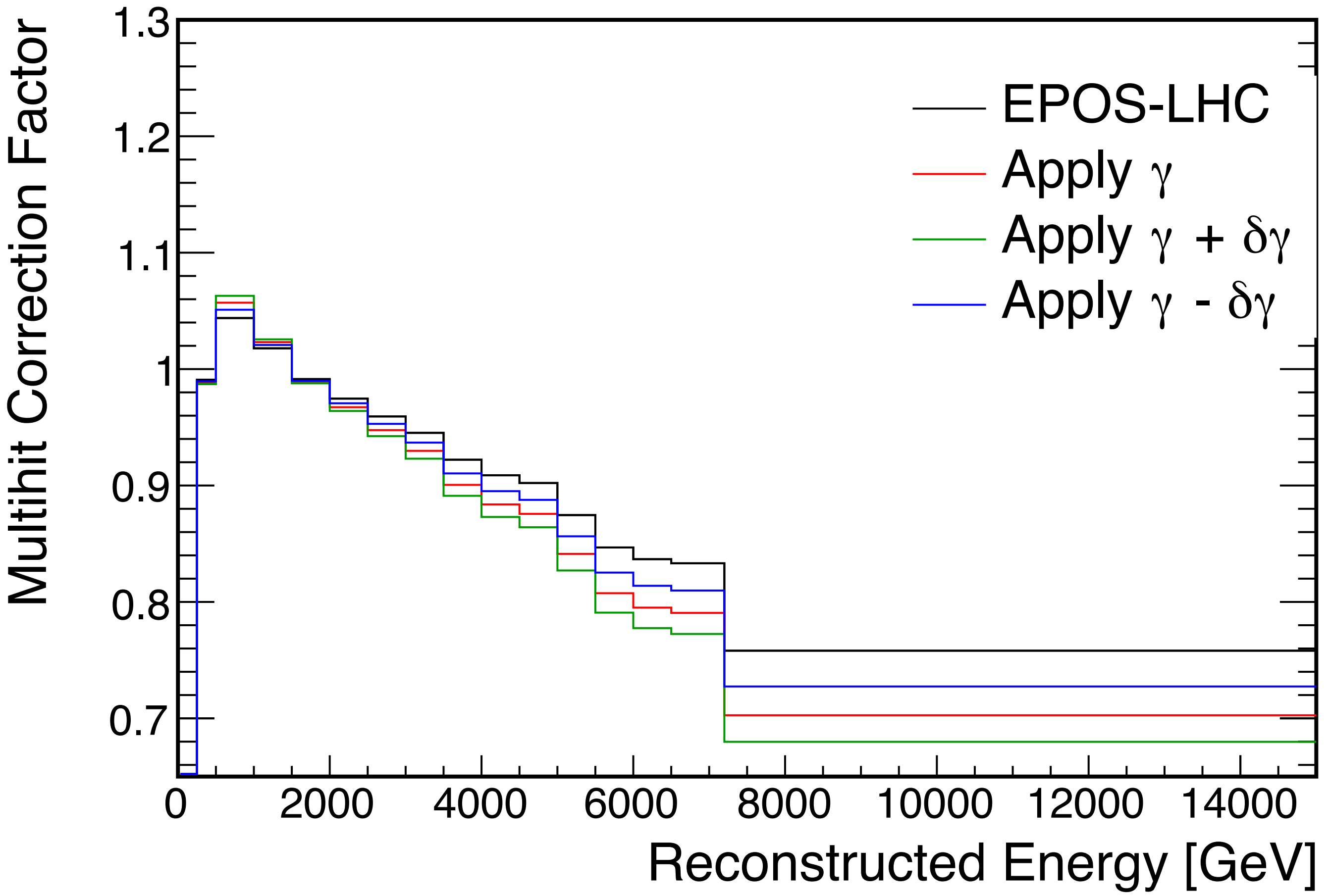


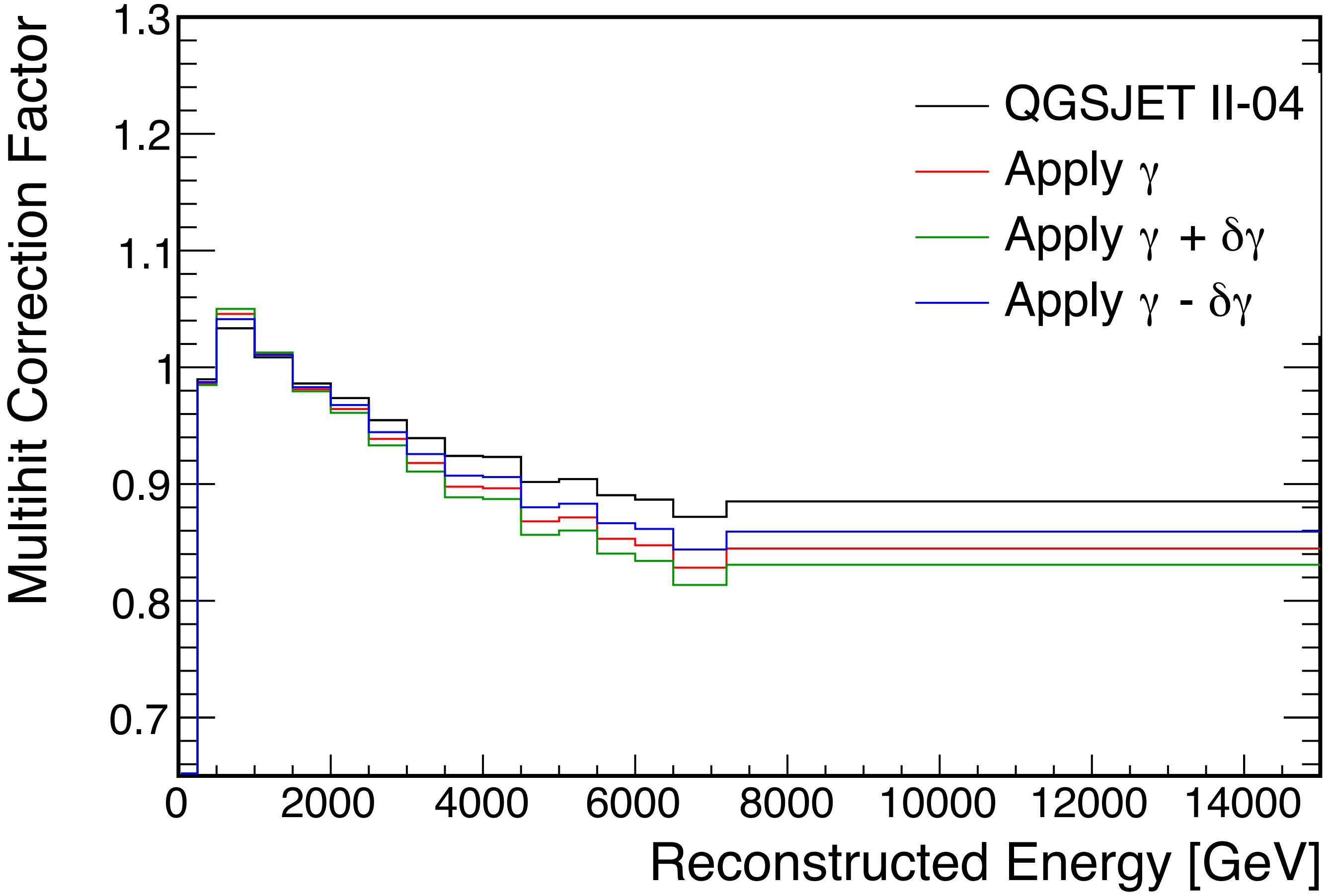
Apply data-driven factors

Multi-hit correction for $10 \leq N_{\text{track}} < 16$

The data-driven factor was applied.





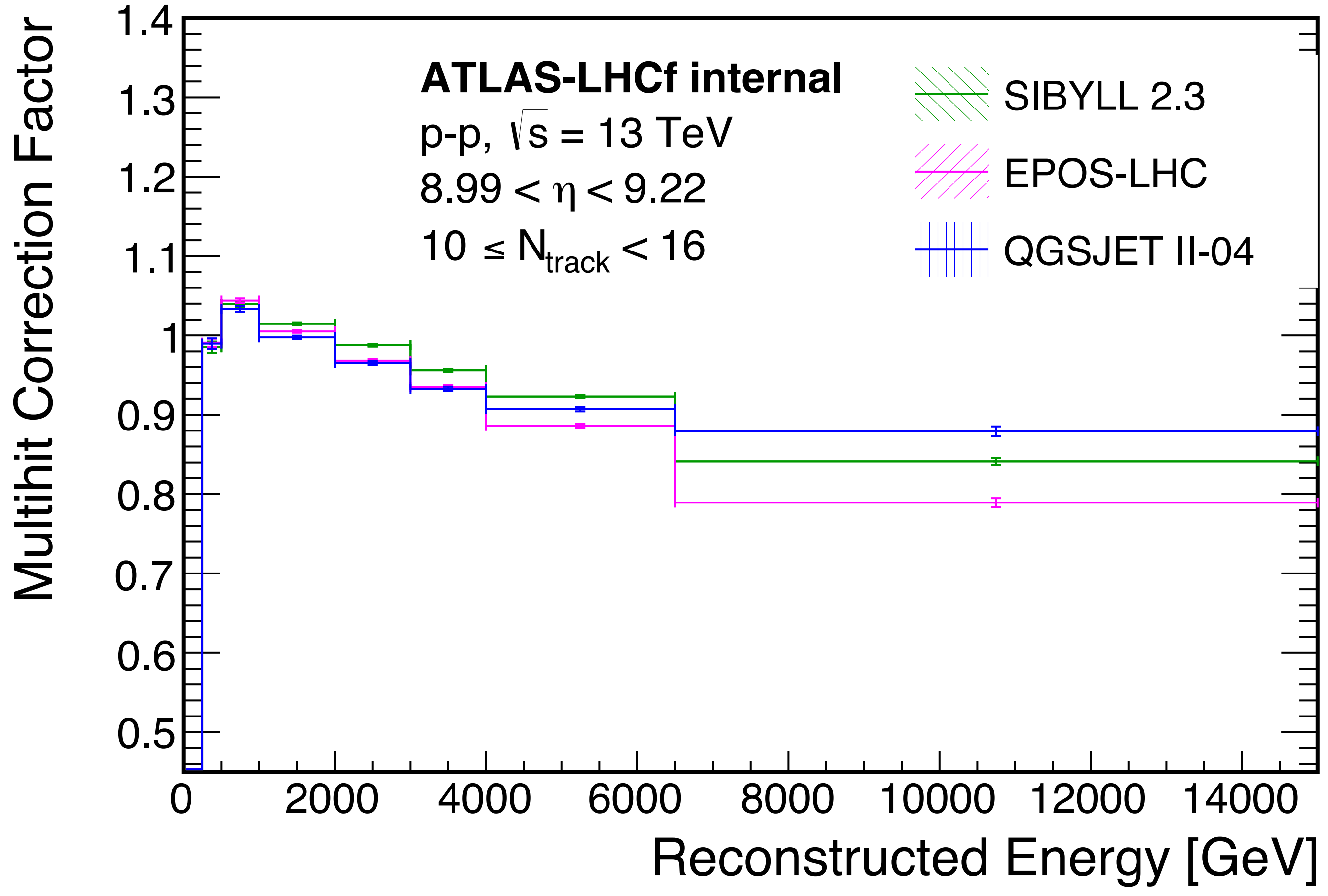


Apply data-driven factors

Multi-hit correction after applying the data-driven normalization factor

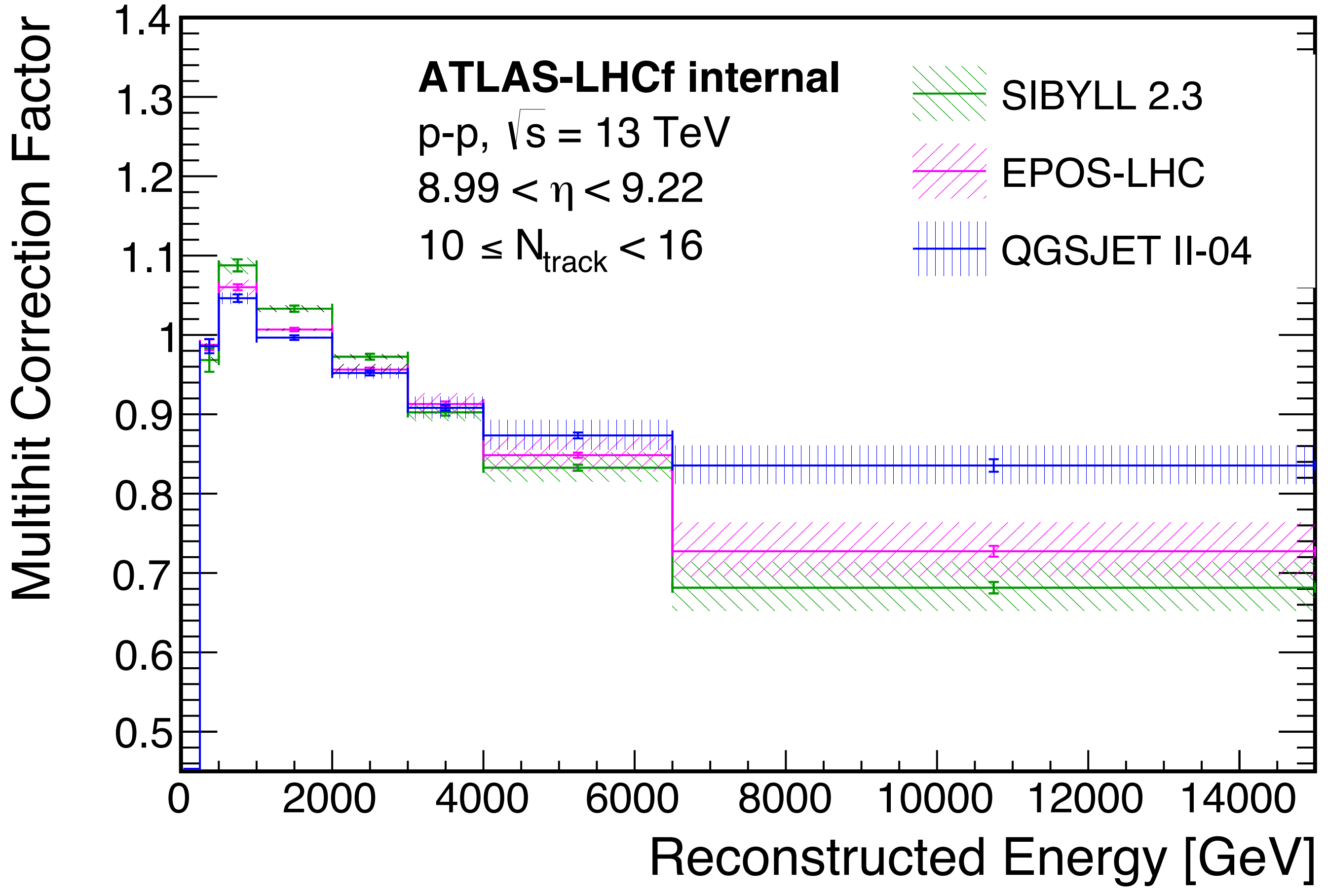
Region 1

No factor applied



Hatched regions: considering errors in factors

Error bar: statistical errors of MC.

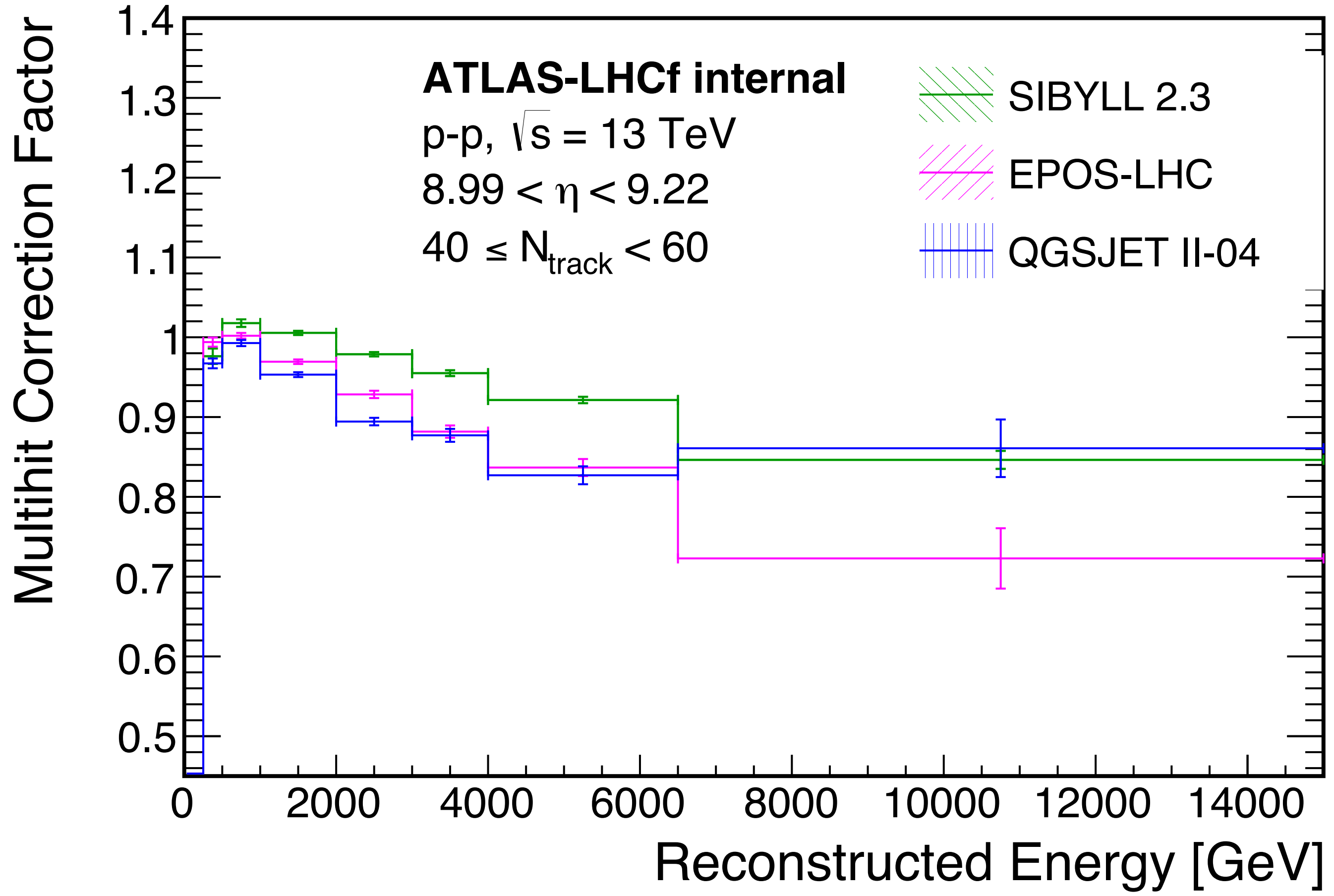


Apply data-driven factors

Multi-hit correction after applying the data-driven normalization factor

Region 1

No factor applied



Hatched regions: considering errors in factors

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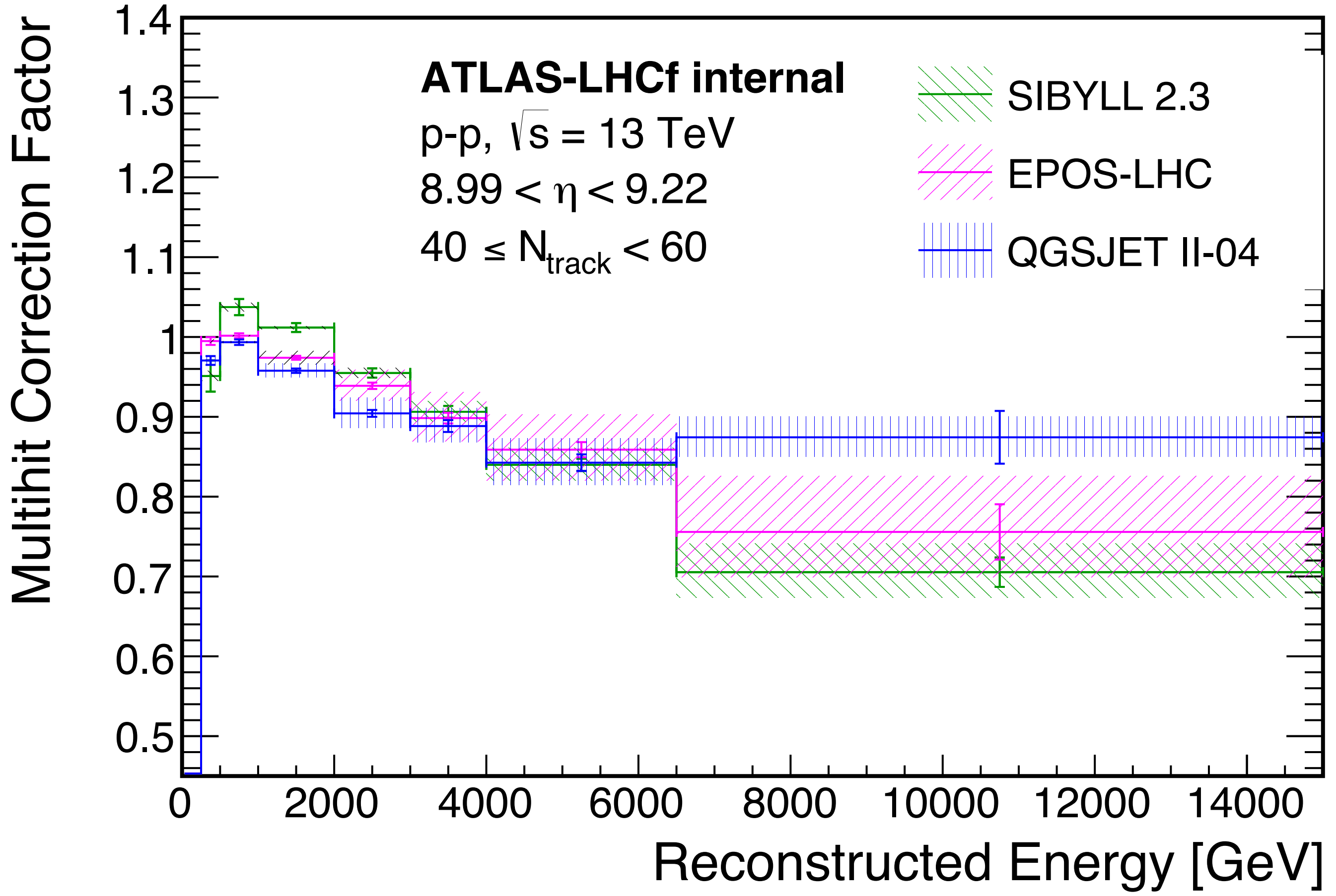
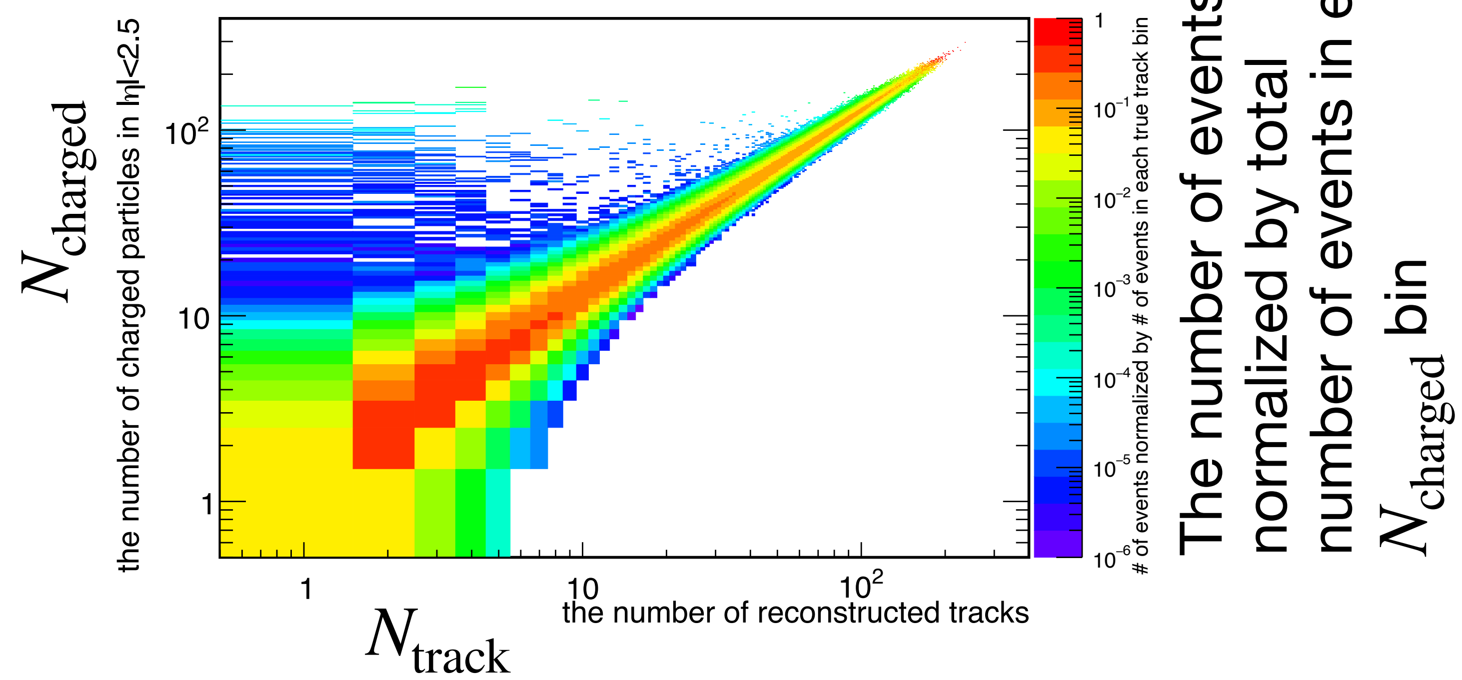


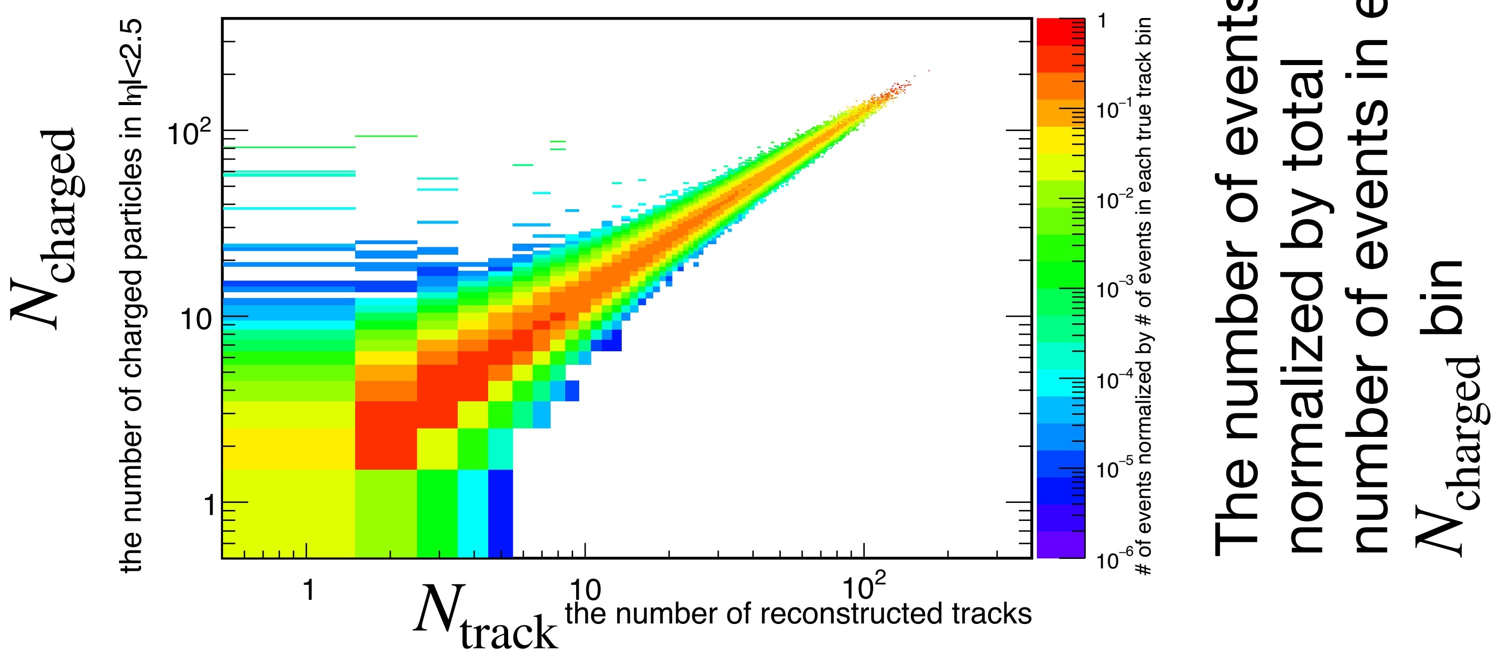
Backup - unfolding

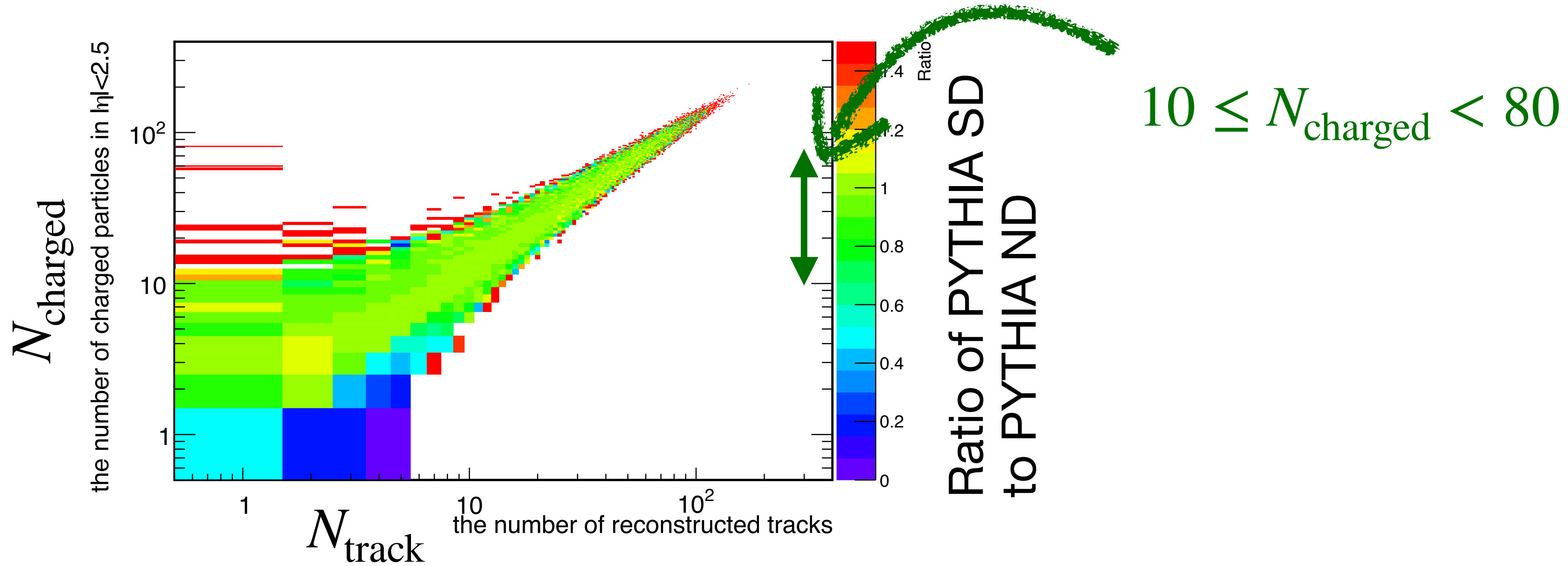
Response matrix for ATLAS tracks

PYTHIA ND



PYTHIA SD



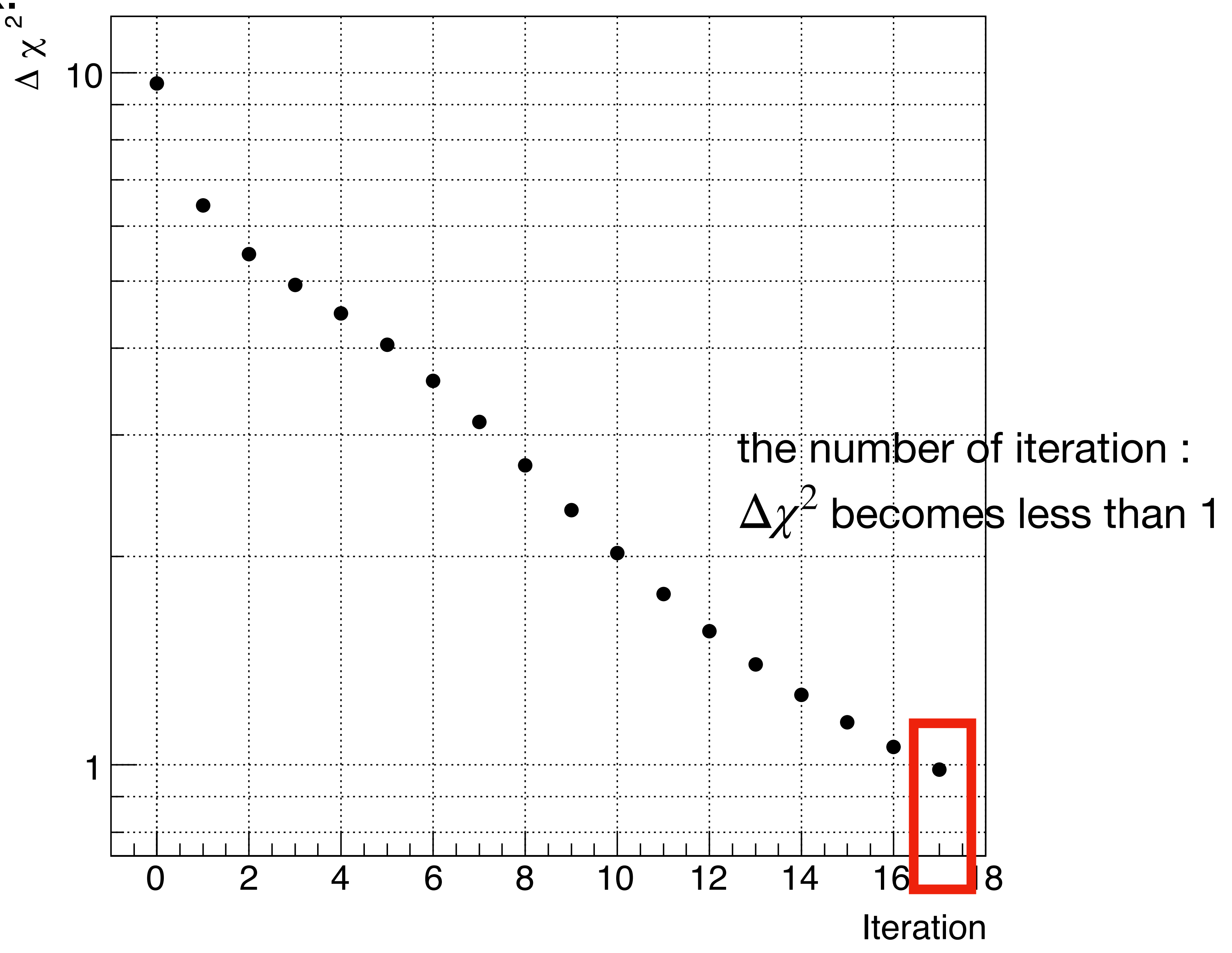


The number of iteration

the number of iteration depends on input spectrum and the response matrix.

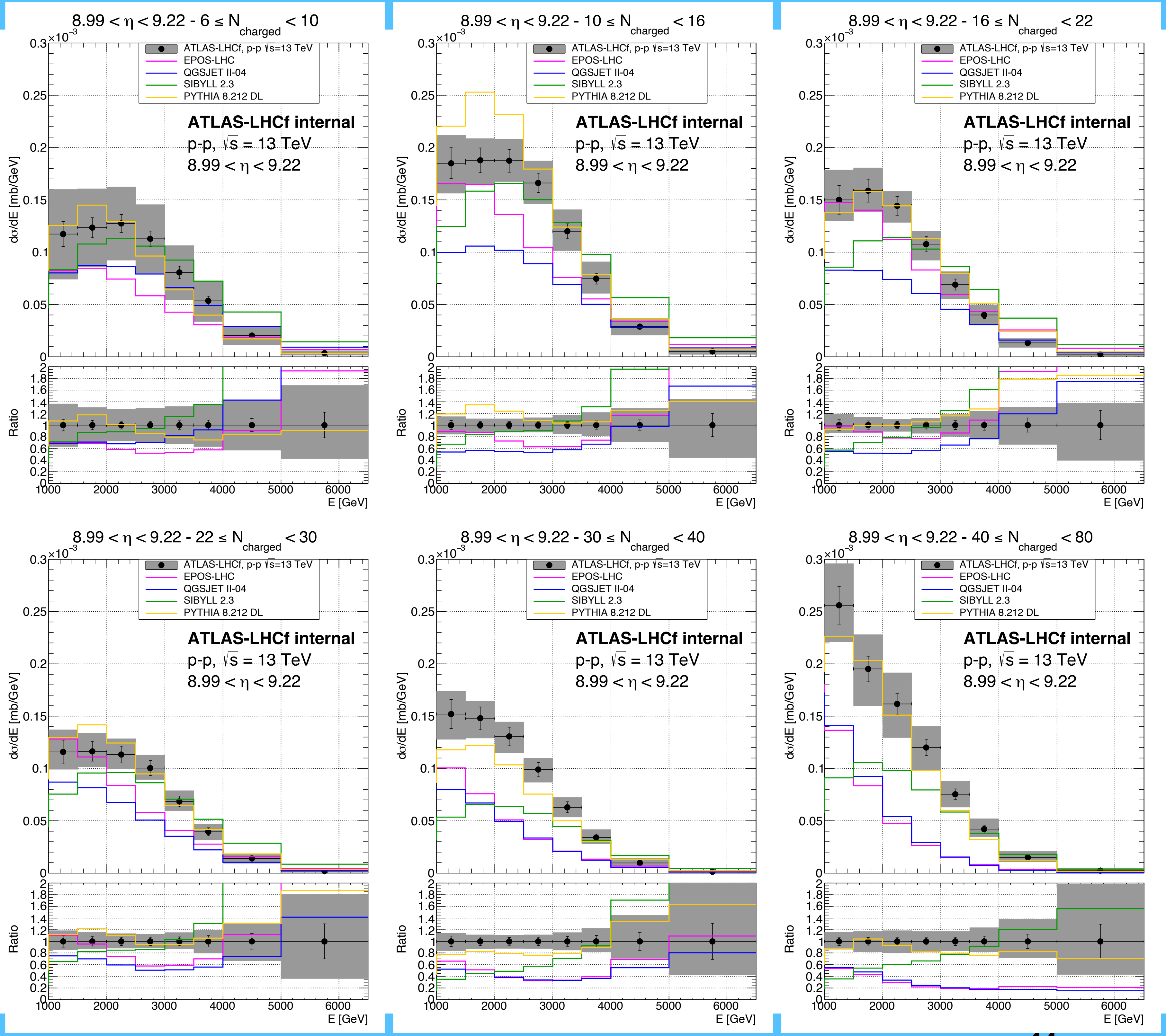
$\Delta\chi^2$: the χ^2 between the outputs of two consecutive iterations

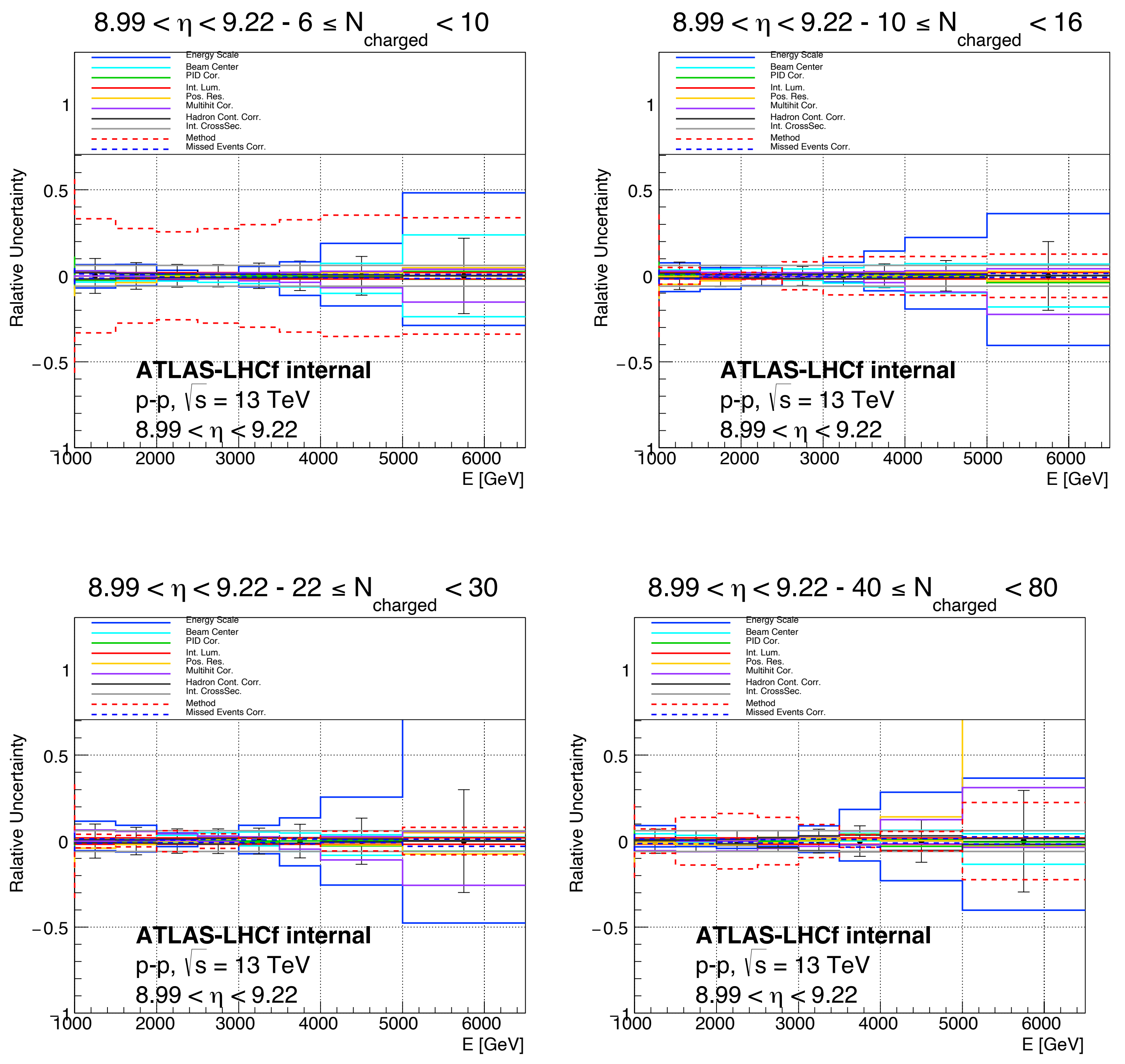
Region 1



Preliminary final results

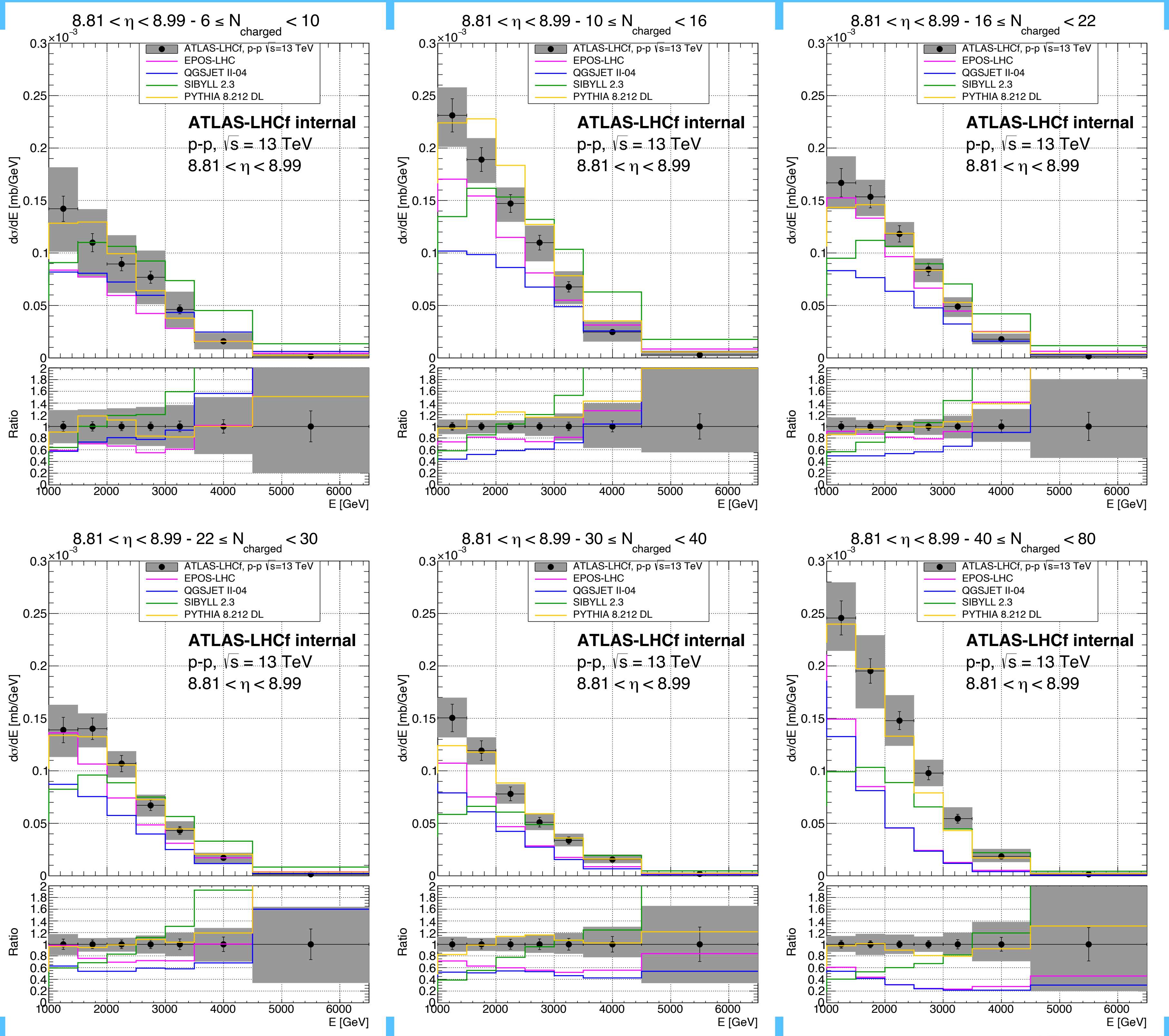
ATLAS soft QCD meeting Feb. 2023

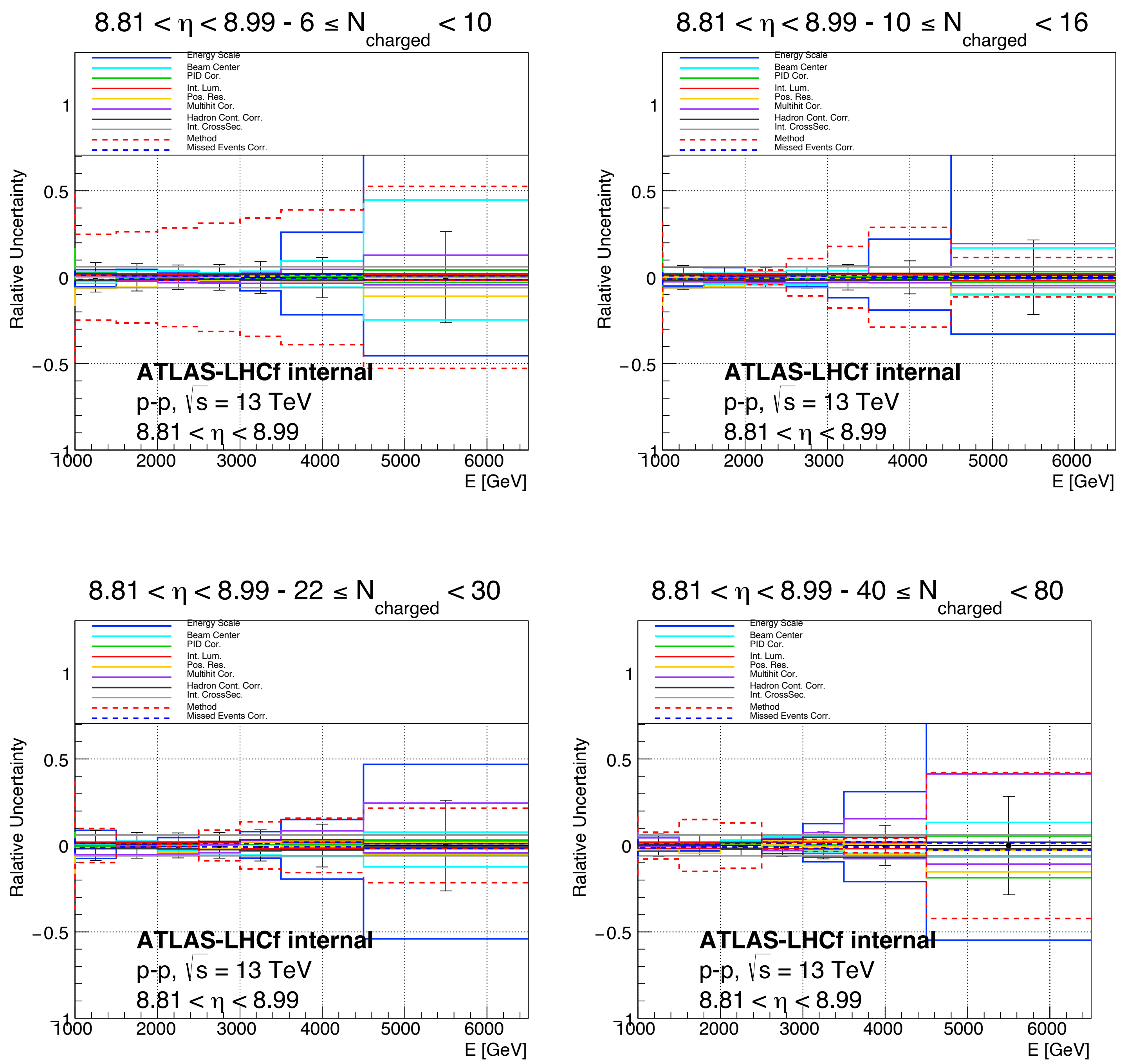




Preliminary final results

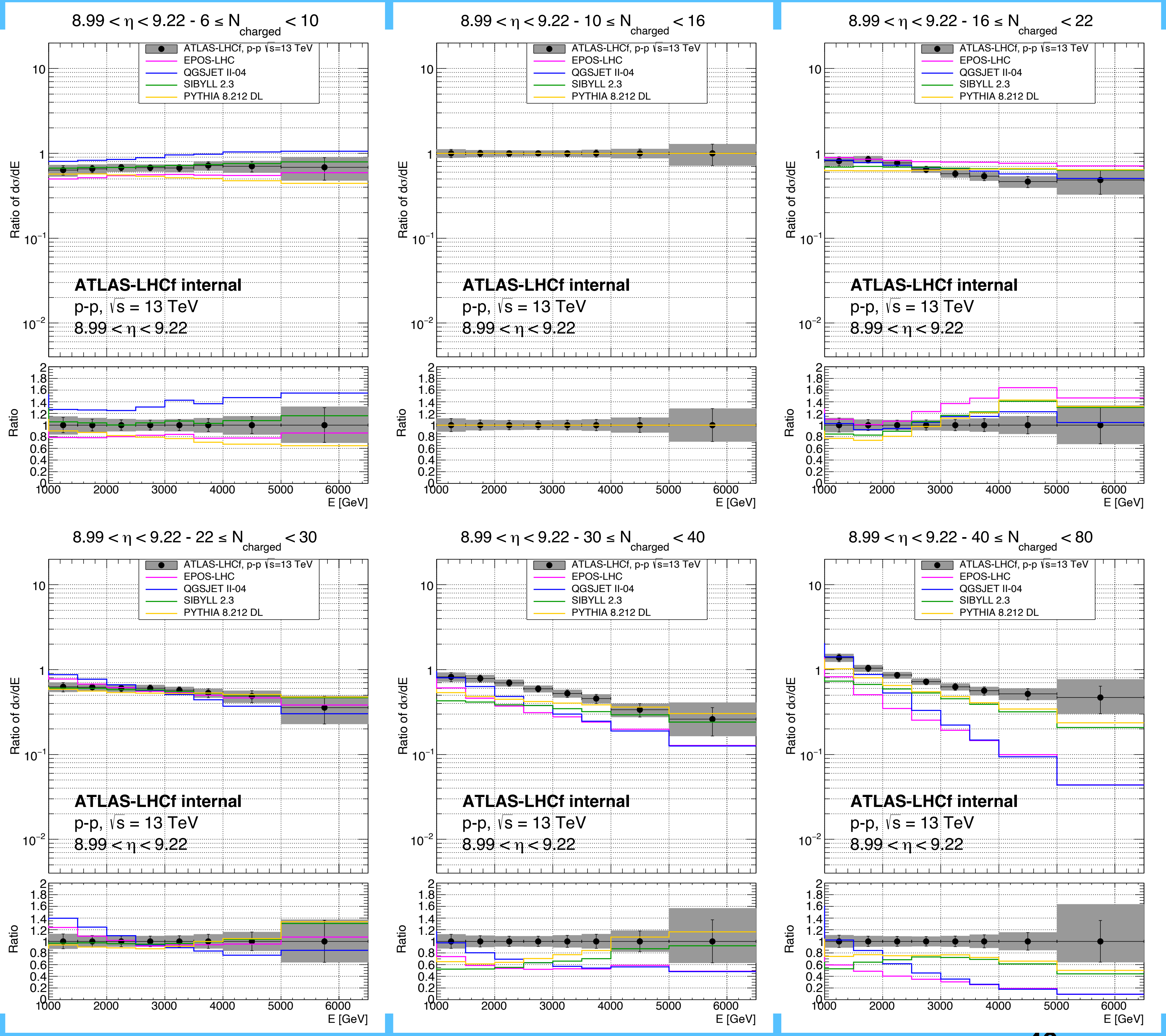
ATLAS soft QCD meeting Feb. 2023

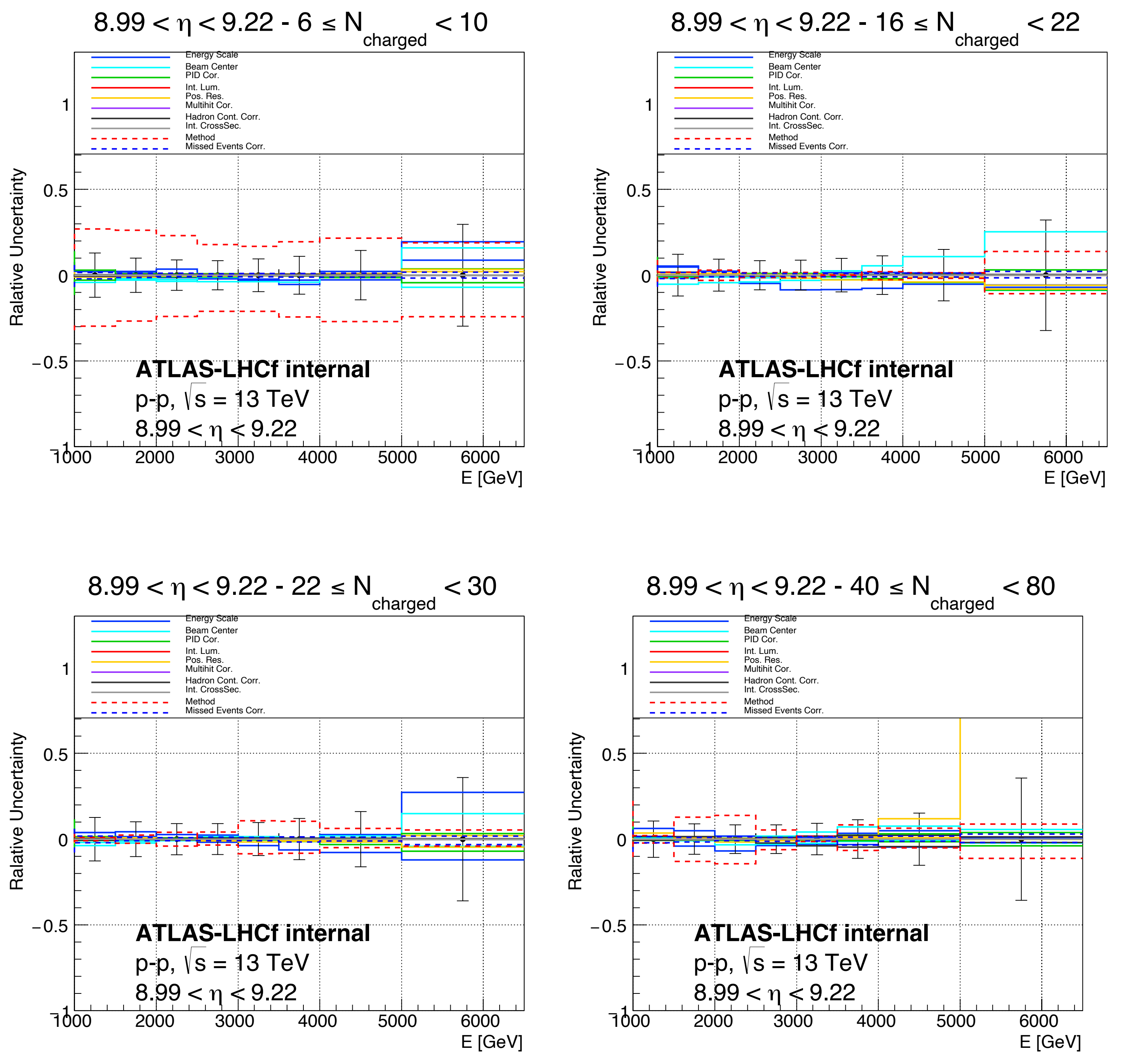




Preliminary final results

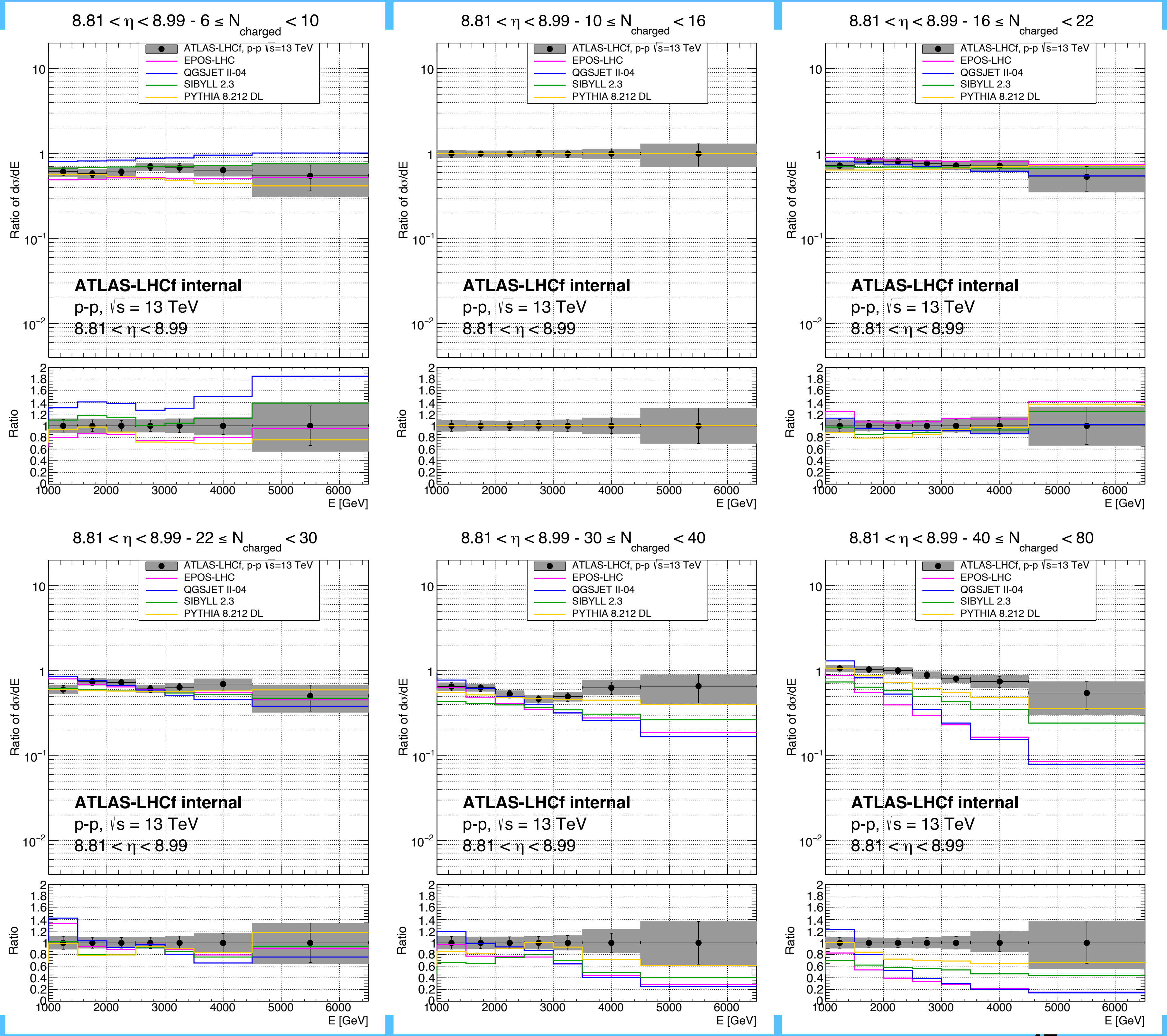
ATLAS soft QCD meeting Feb. 2023

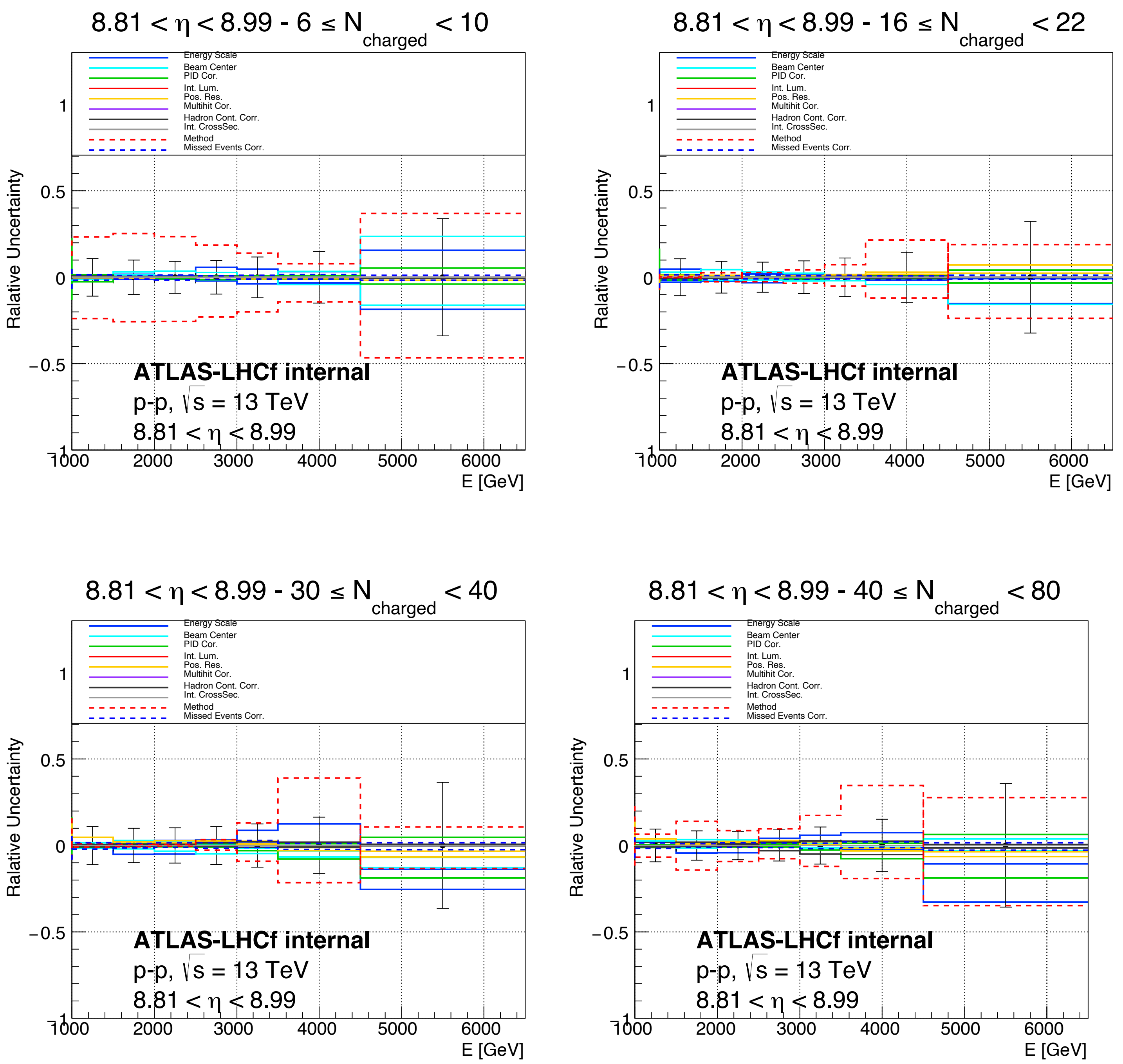




Preliminary final results

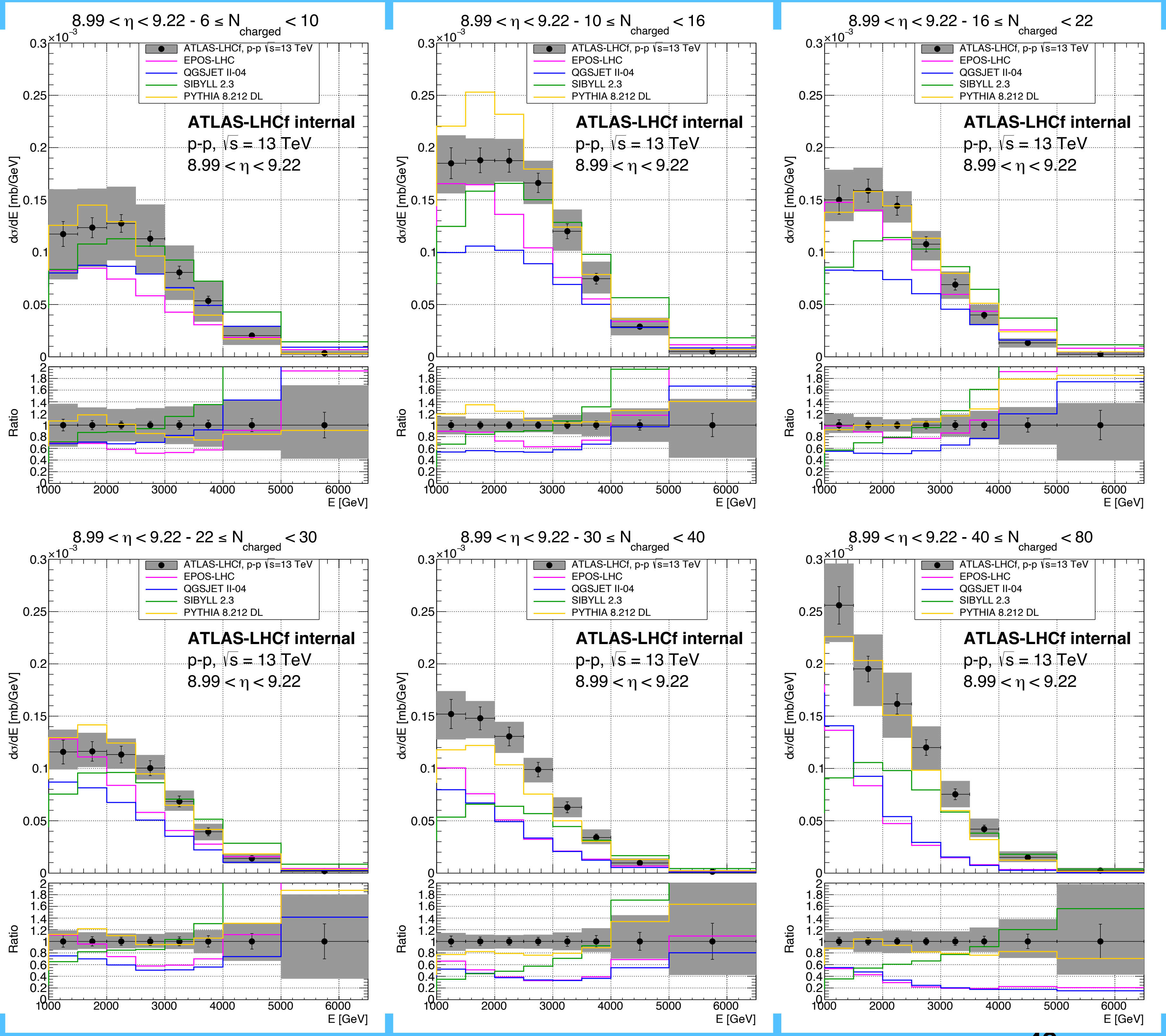
ATLAS soft QCD meeting Feb. 2023





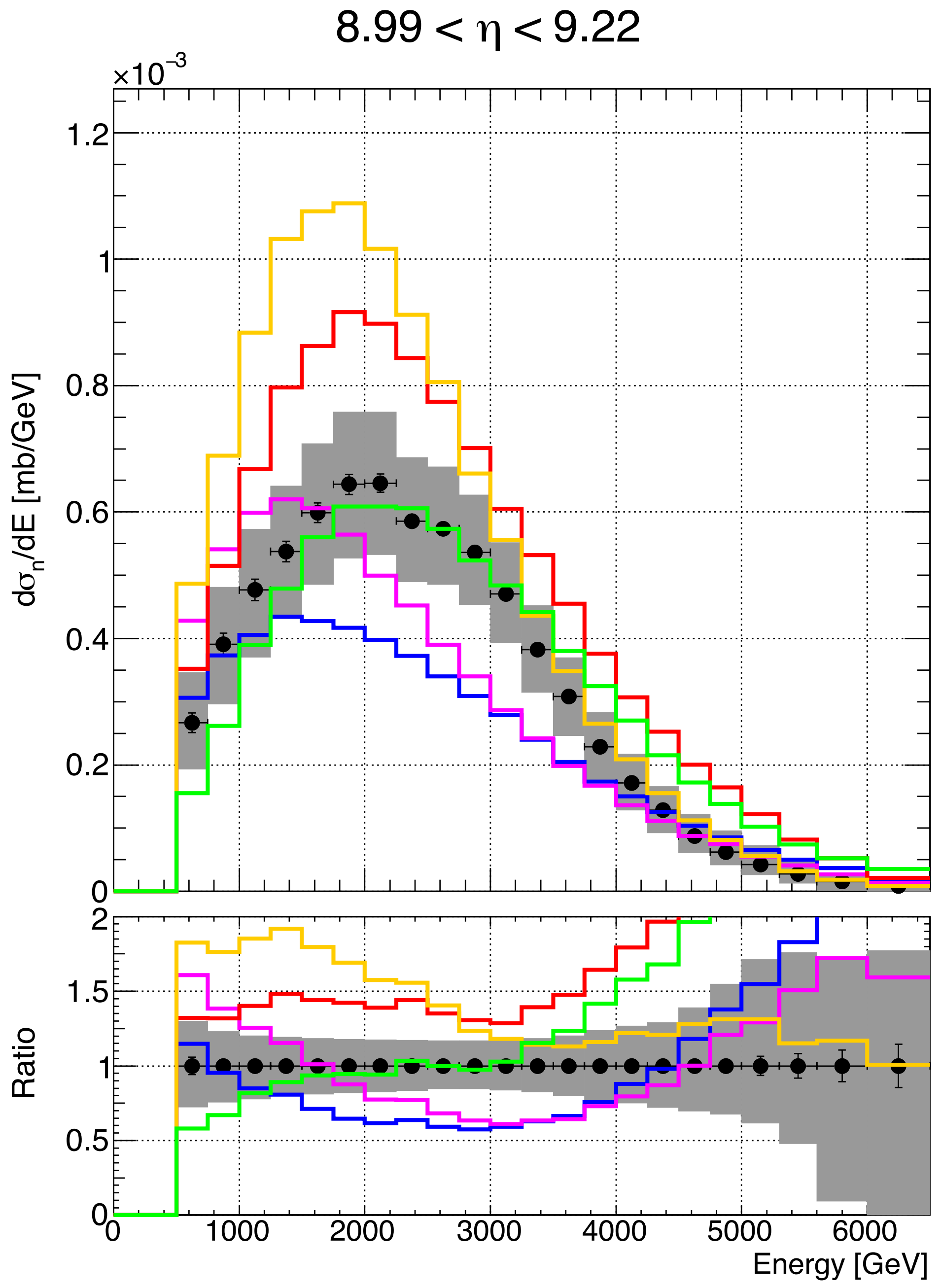
Comparison with LHCf inclusive results

ATLAS soft QCD meeting Feb. 2023



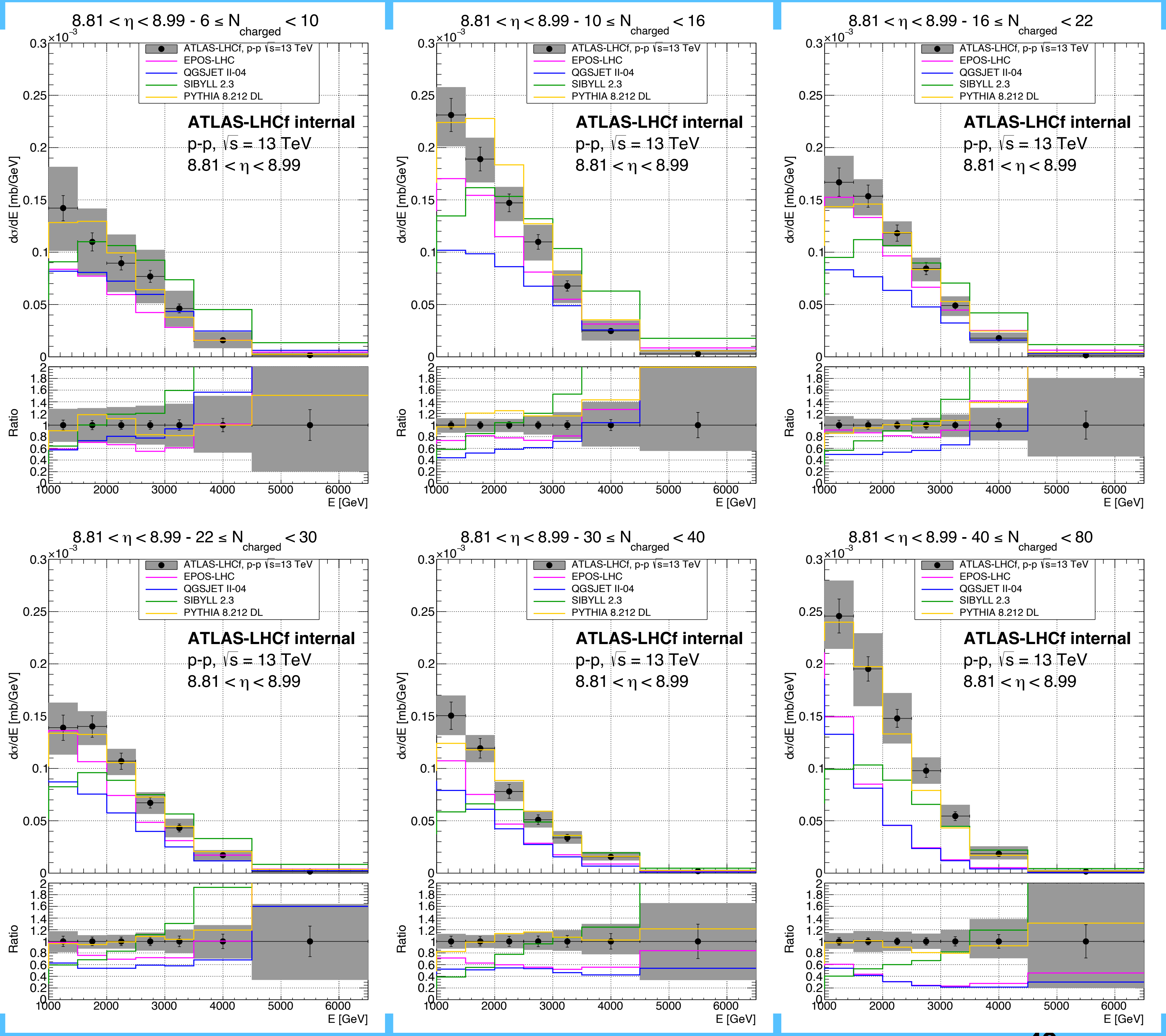
Adriani, O., Berti, E. et al.

J. High Energ. Phys. (2018) 2018: 73



Preliminary final results

ATLAS soft QCD meeting Feb. 2023



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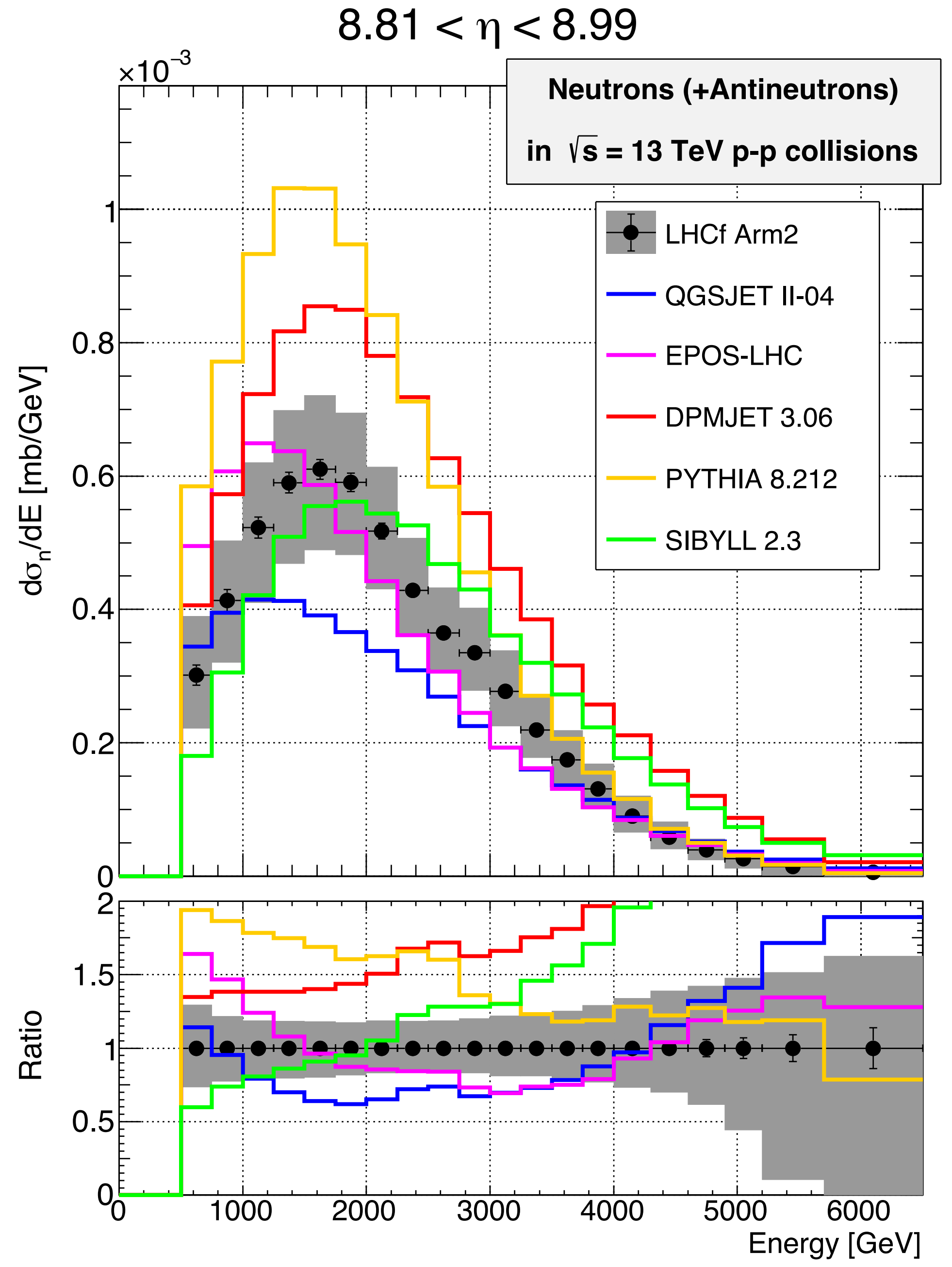


Status of ATLAS-LHCf joint neutron analysis

ATLAS-LHCf working group:
L. Adamczyk(ATLAS), H. Menjo, K. Ohashi (Nagoya Univ.), E.Berti (INFN Florence)

2023 Feb. 20th — ATLAS soft QCD meeting — Ken Ohashi

List of updates from the last report

- Last reports
  - June 2021 — updates of multi-hit corrections and status of unfolding
  - 2022 Apr. 25th — status of multi-hit corrections and candidate of final plots
    - Many comments about multi-hit corrections, unfolding, and fiducial region.
- Updates from the last report
  - Multi-hit corrections: MC-driven corrections with the data-driven tuning of MC
  - Unfolding: performance test and a systematic uncertainty of the unfolding method
  - Final plots
  - Updates related to the comments in the last soft QCD meeting.
    - Add $6 \leq N_{\mathrm{charged}} < 10$ to the final plots
    - Updates in multi-hit corrections
- Remaining works :
  - Minor updates of calculations
  - Validation of all procedures of analysis using ATLAS-LHCf common simulation instead of experimental data.
  - Analysis note

Physics motivation

Three physics motivations of correlation analysis between forward neutrons (LHCf) and central activitiy (ATLAS)

1) : MPI modeling (main target of this analysis)

2) : forward hadron productions from diffraction

3) : One pion exchange process

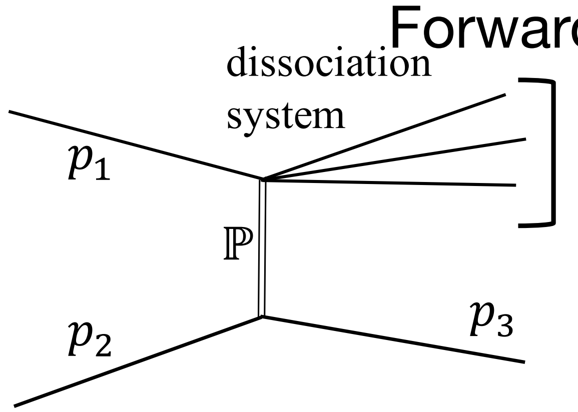
1) modeling of Multi-parton interaction

Different prediction of correlations between remant energy and the number of MPI (details in next slides)

LHCf neutron -> Remnant energy
Ntrack in ATLAS -> Number of MPI

Key to improve prediction power of models for cosmic-ray physics.

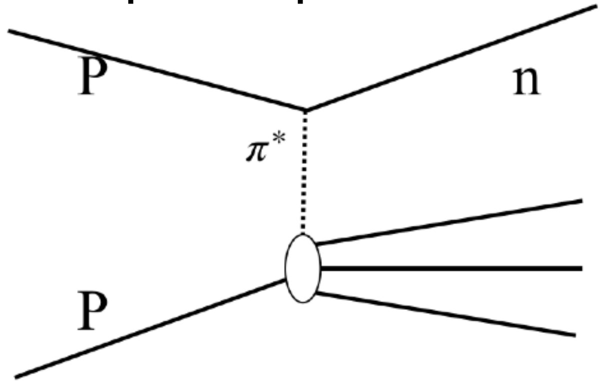
2). Diffraction -> forward neutron



Forward baryon productions in diffraction.

Similar as photon analysis

3). One pion exchange,
Forward neutron
And virtual pion - proton collision



Measurement of p-pi collisions
- cross-section of p-pi
- Multiplicity at p-pi

-> No data in high energy and important for cosmic-ray air shower physics.

Multi-parton interaction

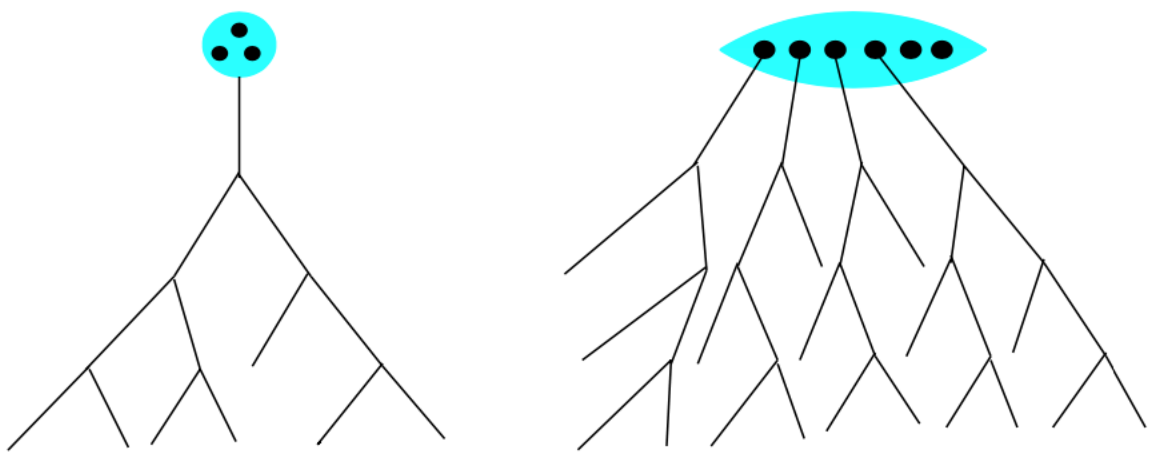
The modeling of multi-parton interaction (MPI) affect central-forward correlation.

Proposed by S. Ostapchenko et al,
Phys. Rev. D 94, 114026

Initial part of Parton cascade are modeled as :

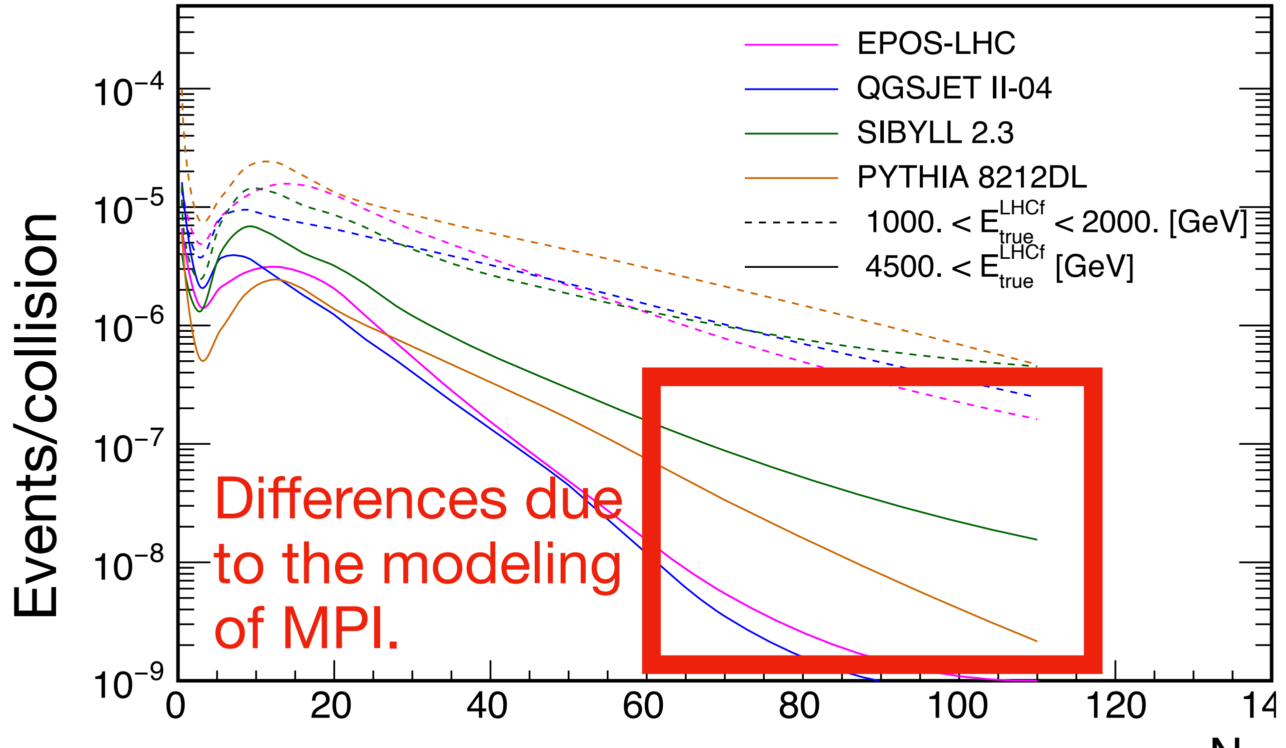
universal state (PYTHIA and SIBYLL)

superposition of partons (EPOSLHC and QGSJET II).



Remnant energy - number of MPI correlation:
Small　　　Large

The number of multi-patron interactions -> N_{ch}
The energy of <u>remnants</u> -> neutrons in LHCf



The number of charged particles in $|\eta| < 2.5$

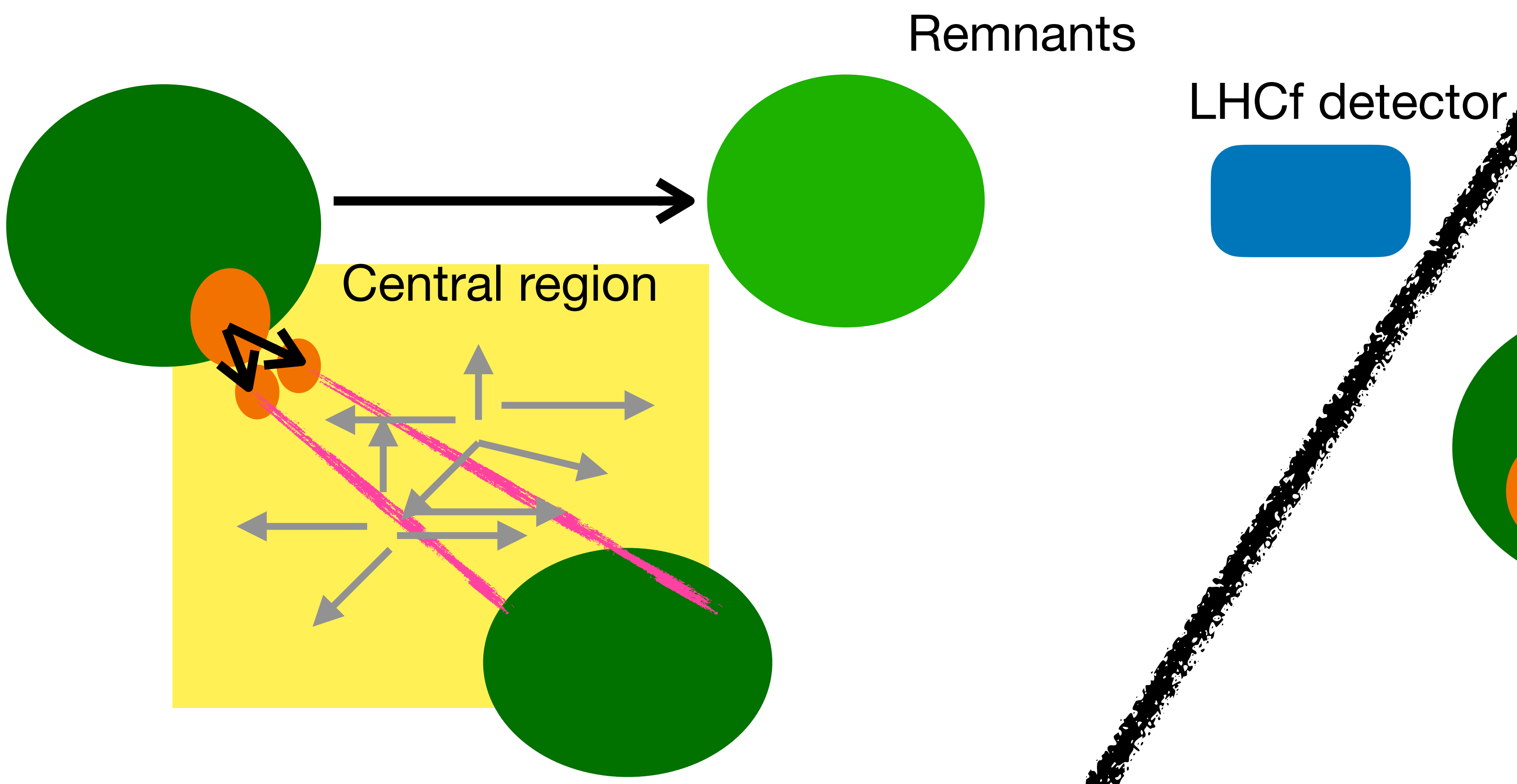
EPOS-LHC and **QGSJET** predict strong central-forward correlation; if high energy neutrons are measured by the LHCf detector, the number of high N_{ch} (high MPI) events is very small.

On the other hand, **SIBYLL 2.3** and **PYTHIA** show weaker central-forward correlation.

Two parton interactions for example

Based on explanations by T. Pierog.

A: PYTHIA and SIBYLL

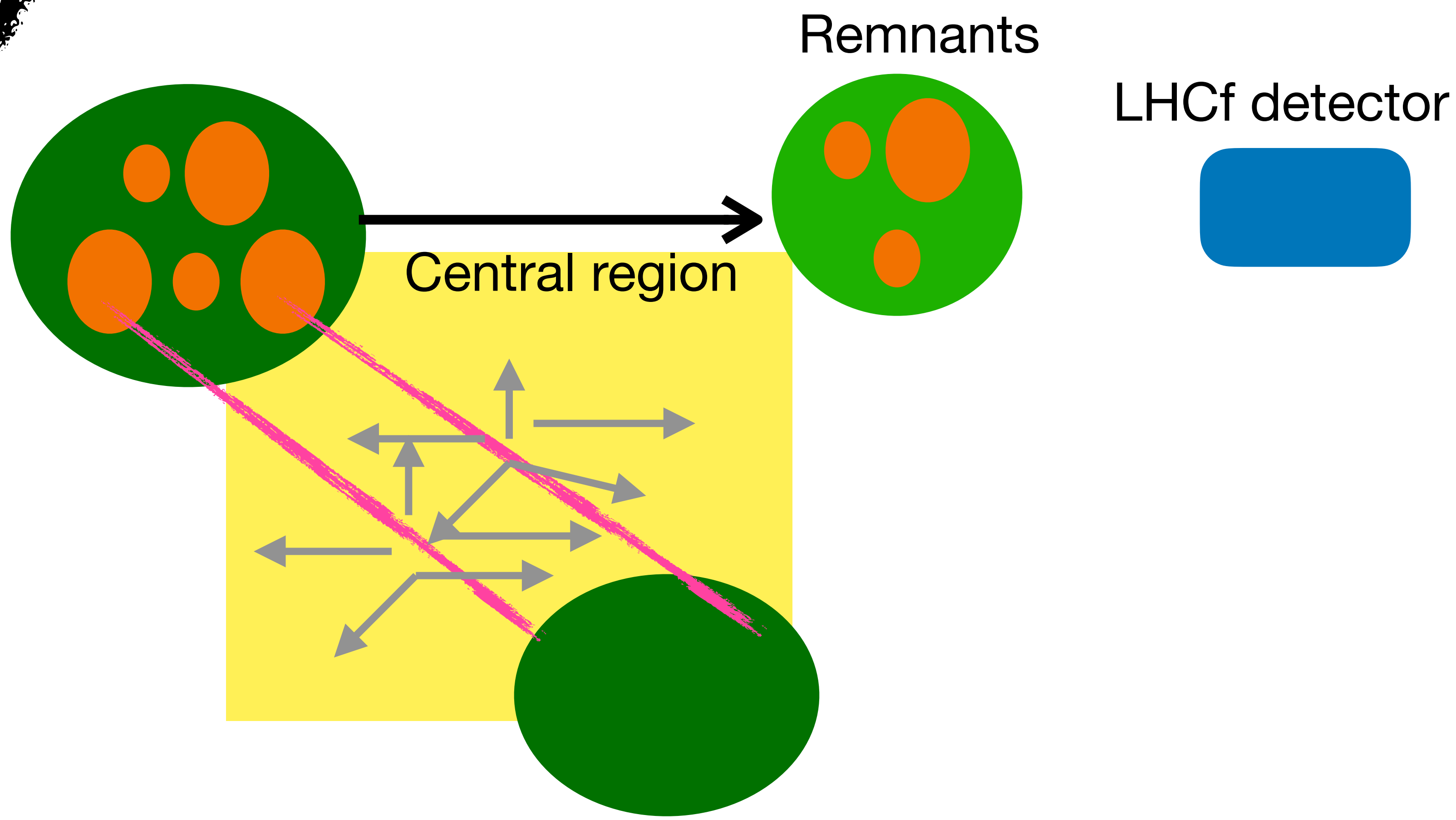


Two parton interactions share the energy of parton.

Motivated as total of MPI energy is calculated from kinematic overlapping of pp

B: QGSJET and EPOSLHC

Each parton interaction is associated with a parton.

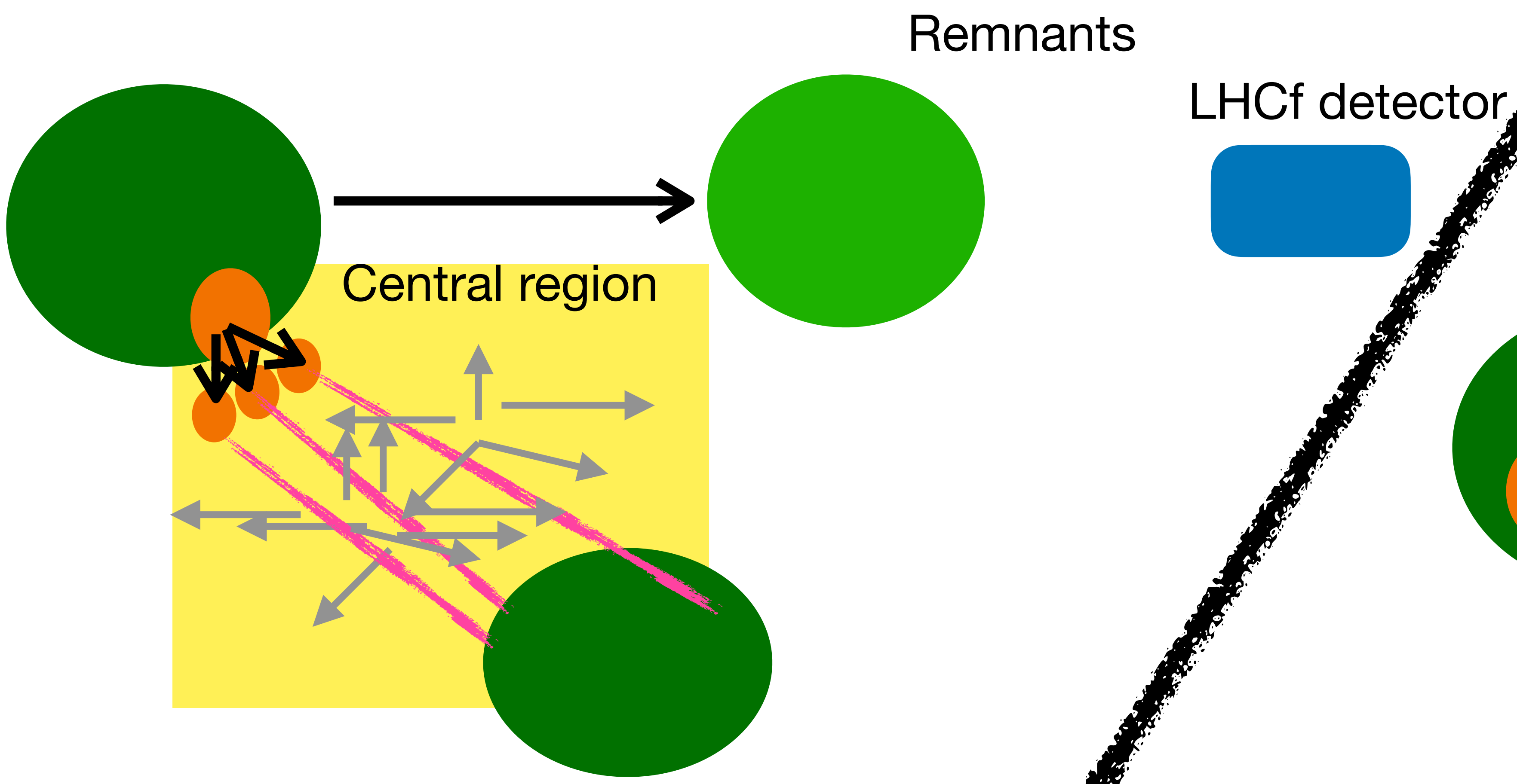


Motivated as MPI is superposition of independent parton-parton interactions.

Three parton interactions for example

<u>**Based on explanations by T. Pierog.**</u>

A: PYTHIA and SIBYLL

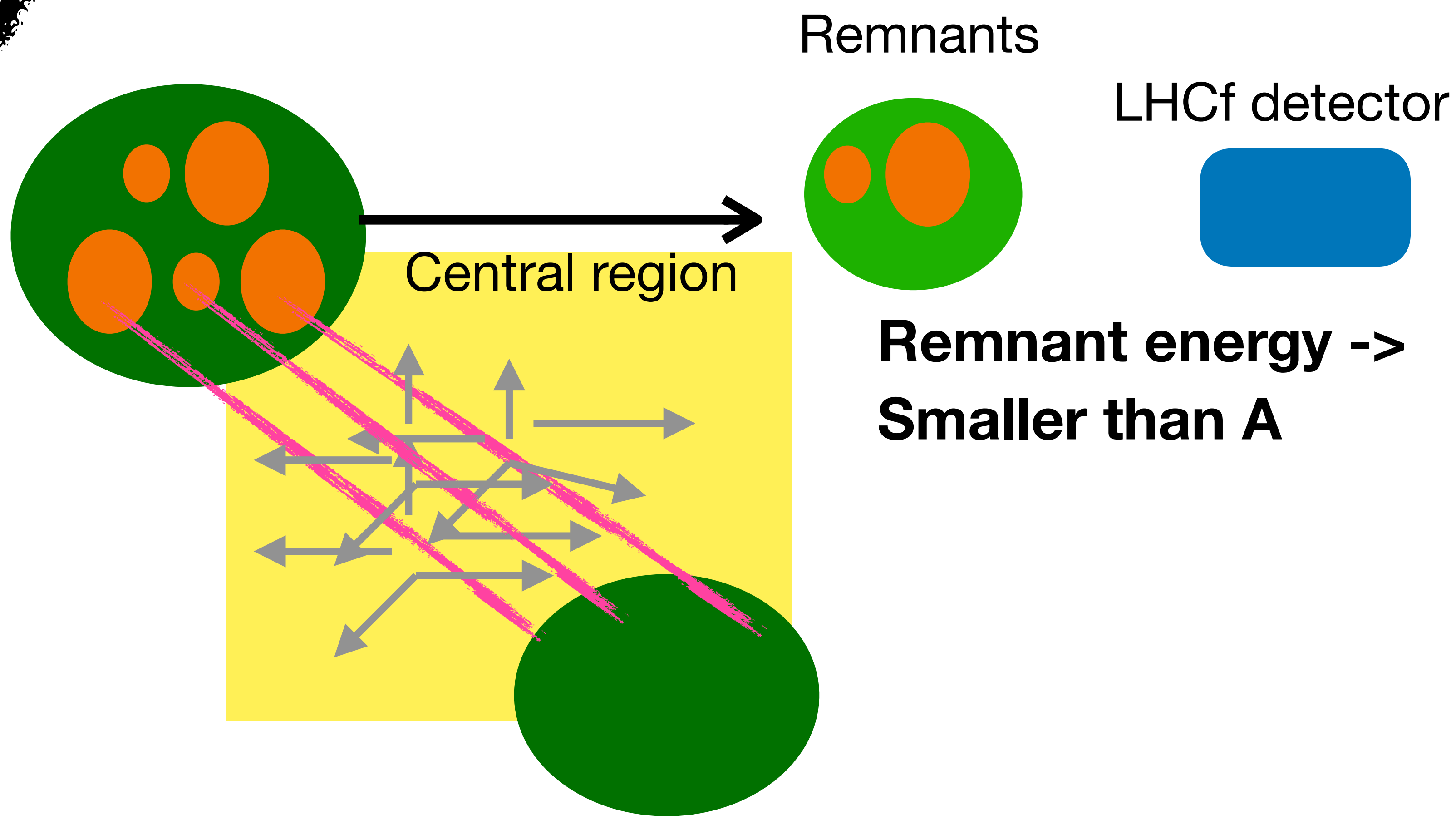


Three parton interactions share the energy of parton.

Energy transferred into central region defined by the energy fraction of one emitted parton.

B: QGSJET and EPOSLHC

Each parton interaction is associated with a parton.



Remnant energy -> Smaller than A

Energy transferred into central region correlated with the number of interacting patrons (= number of MPI)

Analysis strategy and status

Analysis strategy

Extend ATLAS-LHCf photon analysis to LHCf neutron events

ATLAS-LHCf photon analysis

No tracks in ATLAS inner tracker + LHCf photon

(To select forward photons produced by diffraction)

<u>ATLAS-LHCf neutron analysis (This analysis)</u>

Number of tracks in ATLAS inner tracker

+ energy of hadrons in LHCf

<u>Key for this extention</u>

- Multi-hit correction
  - No good identification method of multi-hit for neutrons in LHCf
  - Large model dependency of correction factors
- 2D Unfolding
  - 40% energy resolution (<5% for photons)
  - N_track > 2 (migration and background)

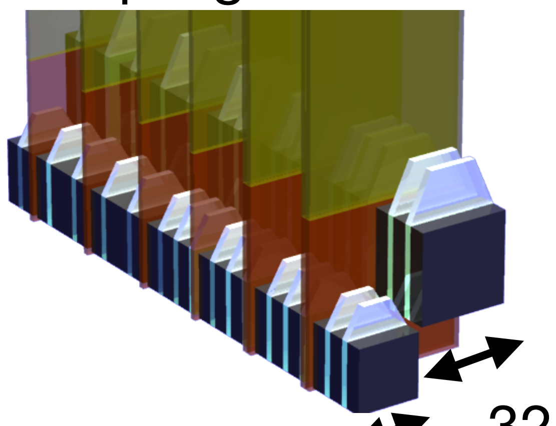
LHCf detector

What we measured: hadrons at 140 m from IP,

neutrons with contaminations of K0 and Λ

LHCf Arm2 detector

Sampling calorimeter



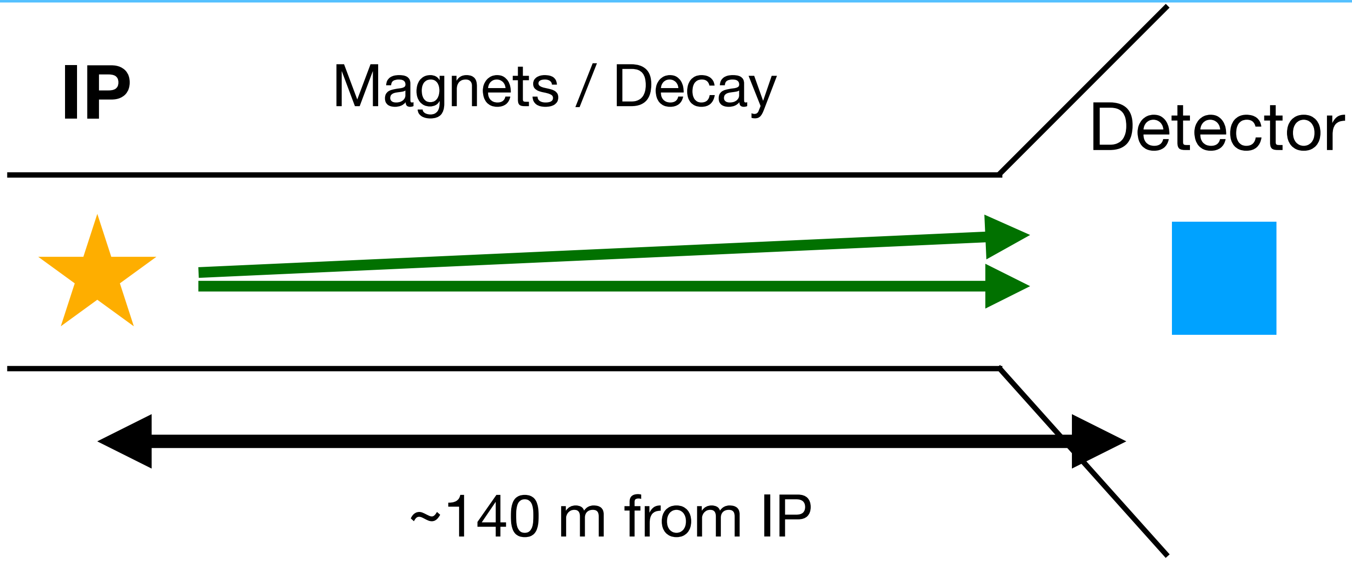
Resolution for hadrons:

- 40% energy resolution

(1.6 interaction length)

- 100 μm position resolution for high energy

- 70% detection efficiency at 2 TeV



Some particles decay in beam pipe

Dataset:

Taken in 2015. $\sqrt{s}$ = 13 TeV.

(from 22:32 to 1:30 (CEST) on June 12-13, LHC Fill 3855)

$L_{int} = 0.191 \pm 0.4\,\text{nb}^{-1}$

MC:

Full simulation: 10^8 collisions (QGSJET), 5×10^7 collisions (EPOSLHC)

Collision + propagation: 10^9 collisions (QGSJET, EPOSLHC, SIBYLL 2.3, PYTHIA 8.212DL)

Artificial MC for the Multi-hit correction factor.

Fiducial regions of the analysis

Fiducial regions

N_{charged} in $|\eta| < 2.5$: $10 \leq N_{\mathrm{charged}} < 80.$

We added plots for $6 \leq N_{\mathrm{charged}} < 10$ following comments in the last meeting.

Energy of hadrons :

Neutral hadrons with $E > 1$ TeV in $8.99 < \eta < 9.22$ (Region 1) or $8.81 < \eta < 8.99$ (Region 2)

At 140 m from interaction points

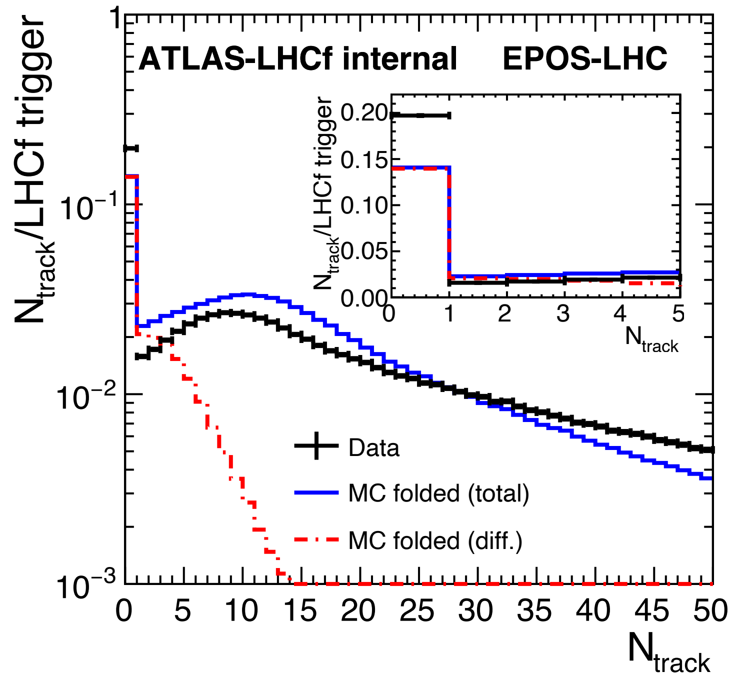


Figure from analysis note for photon analysis

definition of N_{track} was changed.

Black : experimental data.

Red : diffraction (MC)

Blue : all (MC)

In analysis, to consider migrations,

N_{track} in ATLAS inner tracker : $2 \leq N_{\mathrm{track}} < 140$

Energy of hadrons in LHCf :

Hadron-like events with $E_{\mathrm{reconstructed}} > 250$ GeV in $8.99 < \eta < 9.22$ (Region 1) or $8.81 < \eta < 8.99$ (Region 2)

for LHCf-Arm2 detector

Analysis procedure and updates from the last report

Analysis procedure

Event selection

- LHCf detector
  - Hadron-like events using PID
  - $E_{rec} > 250\,\mathrm{GeV}$
  - No multi-hit event selections
- With the number of tracks in ATLAS inner tracker
  - p_T > 0.1 GeV/c, D0 < 1.5 mm
  - “good tracks” definitions
    - Primary vertex, Z0, number of pixel hit etc.

Correction

Background

- Collisions with gas in beam pipe
- Beam pipe materials

LHCf related

- Particle ID correction
- Multi-hit correction
- Position migration correction
- Fake events in LHCf
- Contaminations

After unfolding

- Miss events in LHCf

Most of correction and systematic uncertainties are calculated.

We found large model dependencies in Multi-hit correction. -> next section

Unfolding

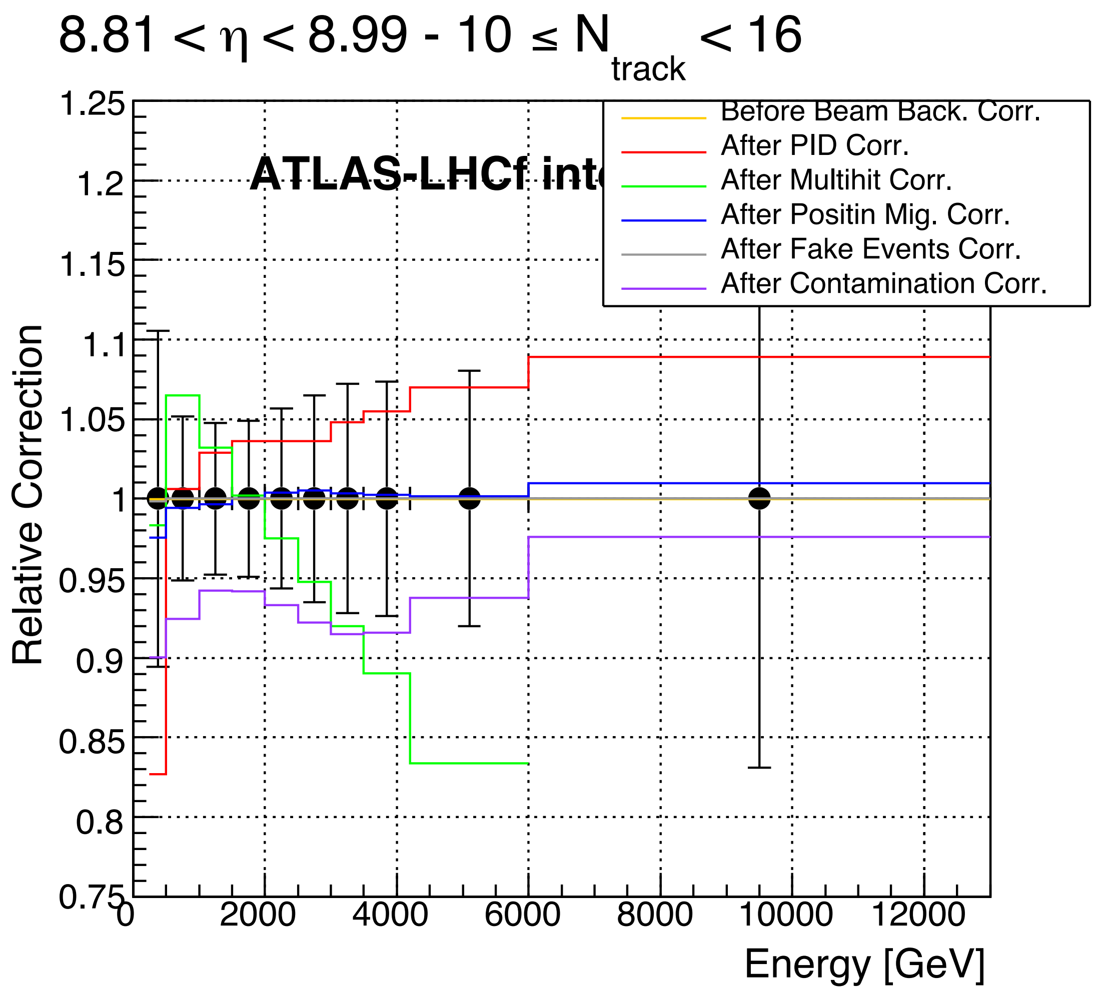
$$(E_{rec}, N_{track}) \rightarrow (E_{true}, N_{ch})$$

The method developed in LHCf-Arm2 analysis was implemented.

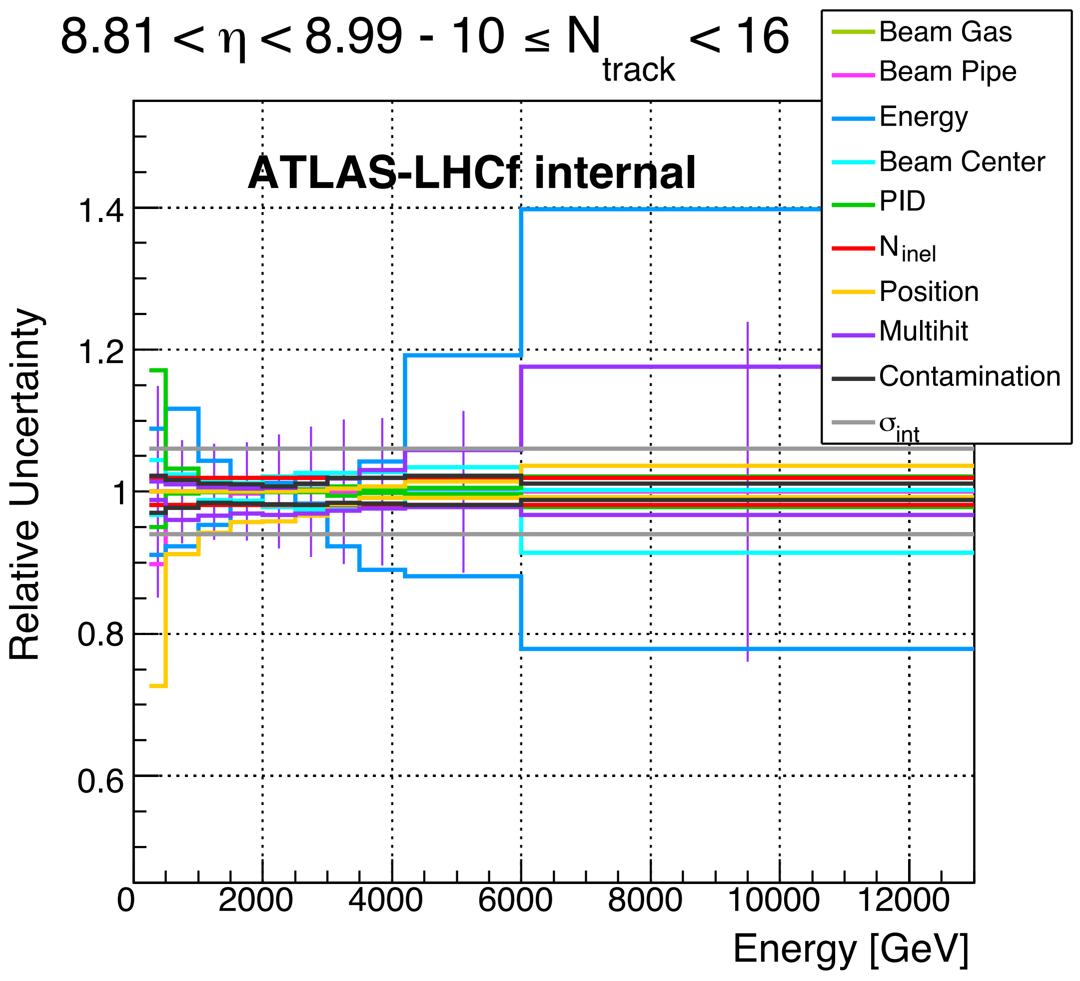
Status of corrections and systematic uncertainties

Results before unfolding

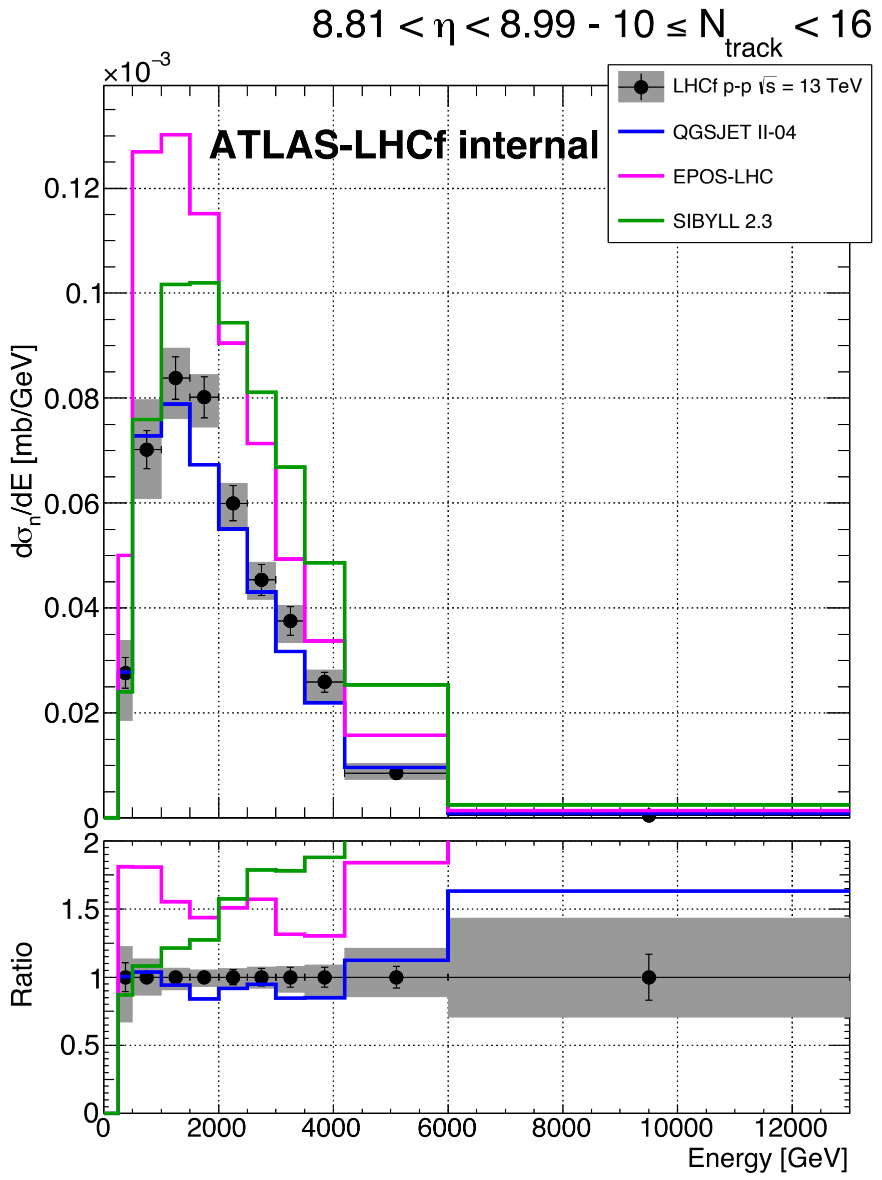
Correction factors



Systematic uncertainties



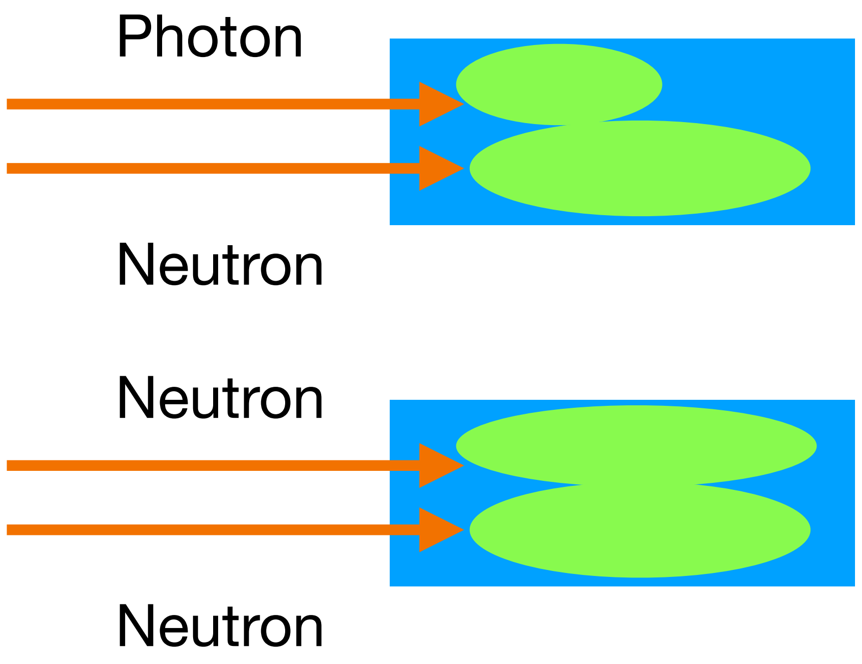
Spectrum before unfolding



Multi-hit correction

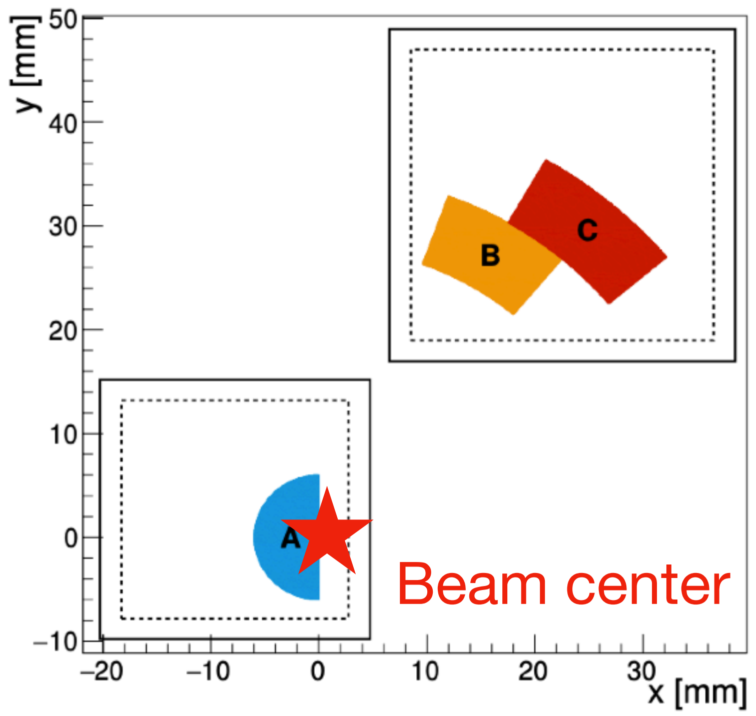
Multi-hit events in LHCf

Sometimes, two particles hit in a calorimeter tower



Current reconstruction produces in LHCf detector:
We cannot reject multi-hit events with hadron and photon or two hadrons hit in a calorimeter tower.

LHCf-Arm2 detector and analysis region



These multi-hit events affect reconstructed energies.

In LHCf-Arm2 stand alone analysis, these effects are corrected by MC-driven correction factors.

Method used in LHCf analysis

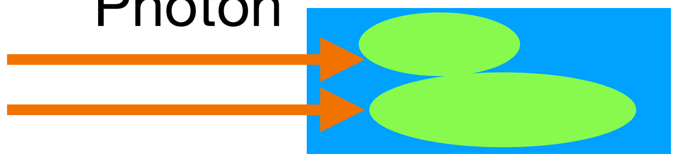
MC driven

Large hadronic interaction model dependencies

<u>Correction was calculated using two simulation:</u>

Simulation (observed)

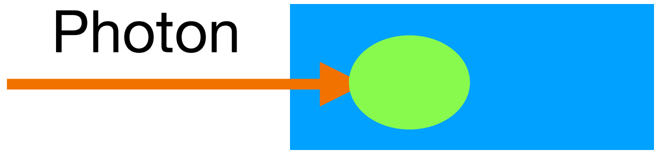
Photon



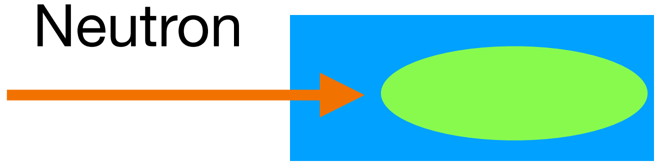
Neutron

Simulation (ideal)

Photon



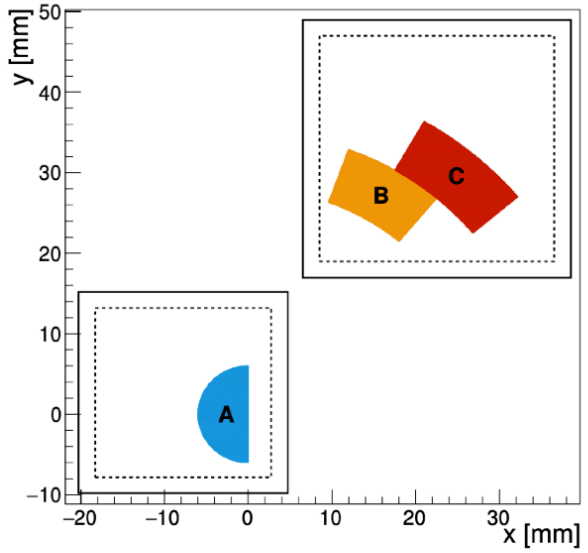
Neutron



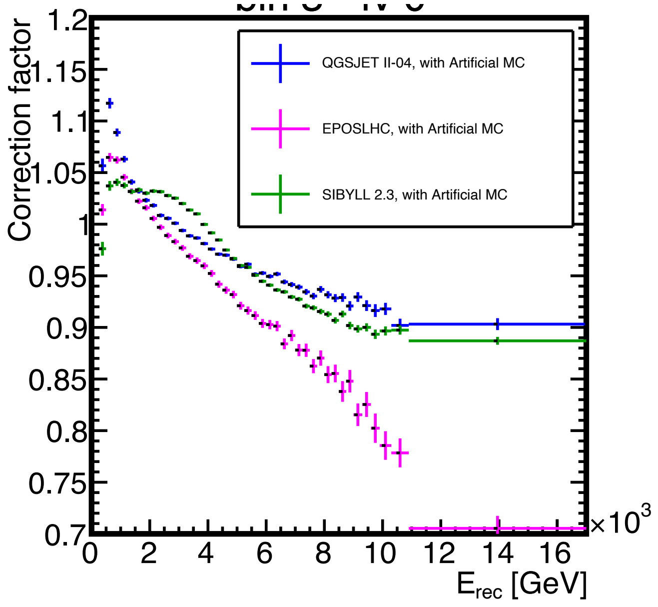
Compare two energy spectra

Multi-hit correction factor

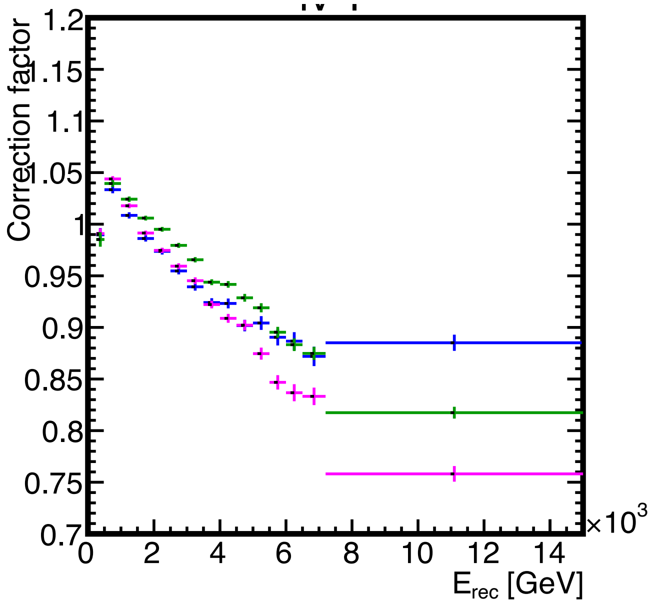
Three analysis region



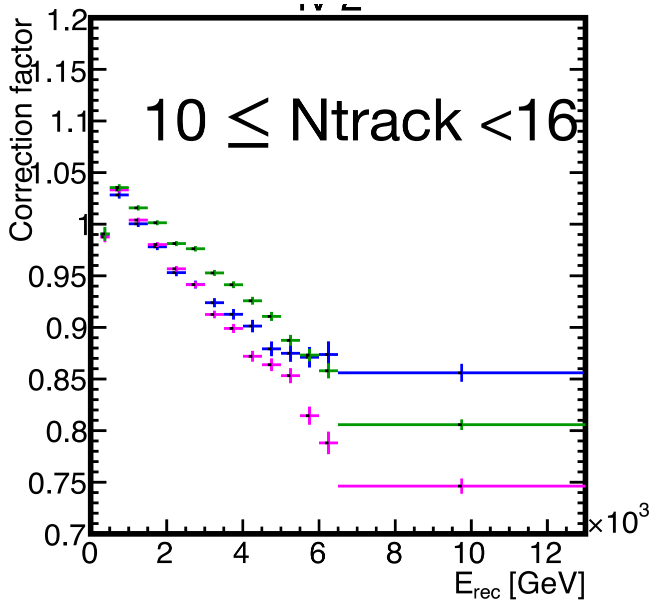
Region A



Region B



Region C



Reconstructed energy [GeV]

<u>Large model dependencies</u>

Magenta : EPOSLHC

Blue : QGSJET II-04

Green : SIBYLL 2.3

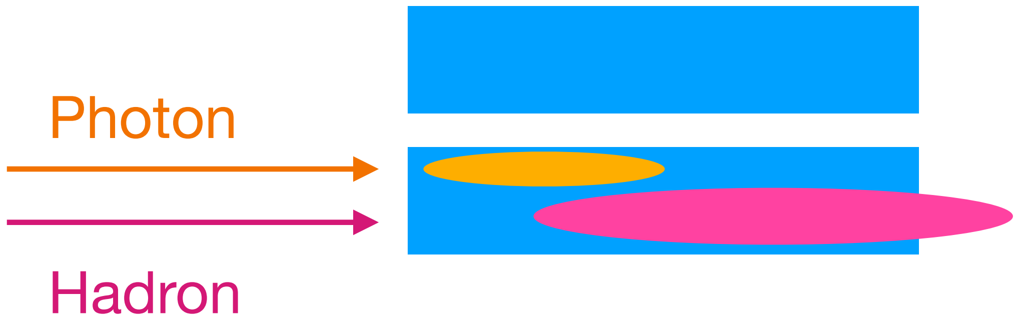
Status of multi-hit corrections

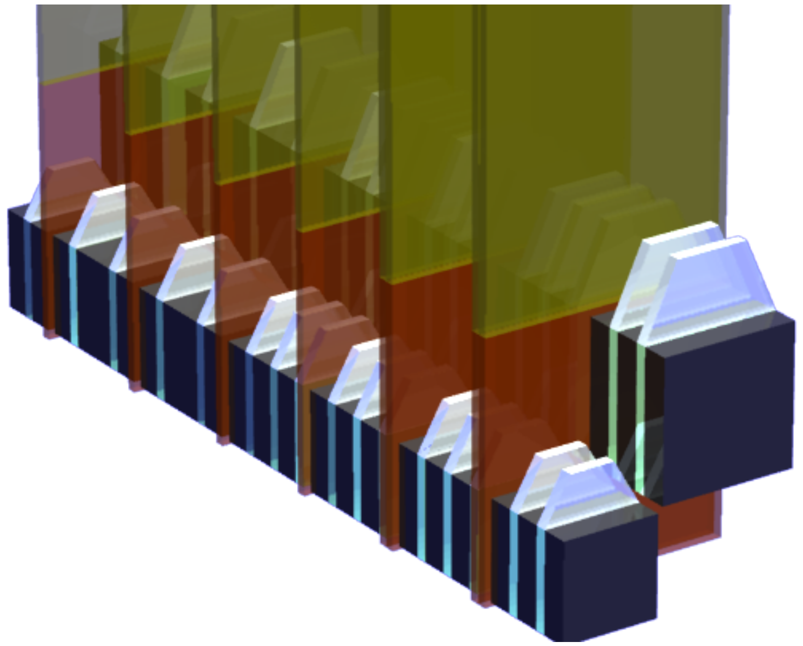
- In the LHCf stand-alone analysis, the corrections were calculated by the MC-driven method.
- Clearly, we have large uncertainty due to hadronic interaction models.
- We tried several ways to validate and tune the hadronic interaction models.
    - In the last report on 2022 Apr. 25th, we reported one method using the experimental data.
    - But uncertainty in the method was too large.
- In the discussions with ATLAS members on May 2022, we got another idea.
    - The first several layers of the LHCf detector are useful to select multi-hit events.
    - So, we try to select multi-hit enhanced events and then validate hadronic interaction models.
    - Finally, we calculated a data-driven normalization factor for multi-hit contributions.
    - Then, we calculated multi-hit corrections in the MC-driven method but with tuning of MC predictions.

Validation and tuning of multi-hit predictions

Using first 6 layers as veto of multi-hit events

- In multihit events with photon and hadron in a tower,
  - An electromagnetic shower develops in early parts of the calorimeter tower.
  - A hadronic shower develops in later parts of the calorimeter shower.
  - So most of h + γ multihit events, energy deposits in early layers are expected.
- Idea
  - Make multi-hit reduced/enhanced samples using energy deposits in early layers.
  - Then, validate MC predictions from comparison of energy spectra of these samples.

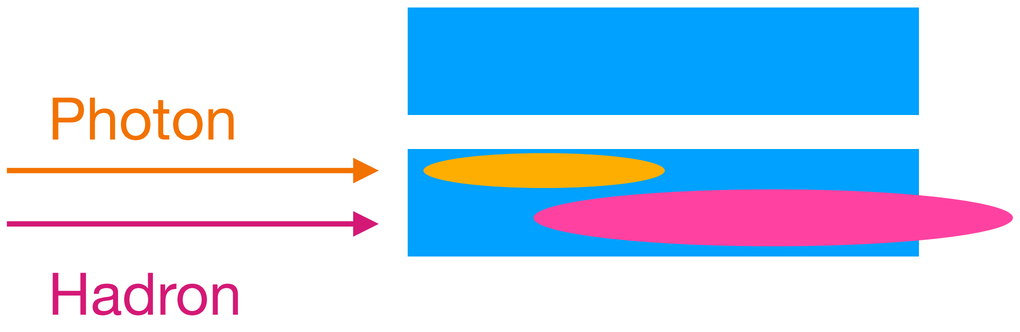




Position sensitive layers before layer 2/5/8
=> energy deposits in layer 2,5,8 were affected.
(Larger gaps between tungsten and scintillator.)

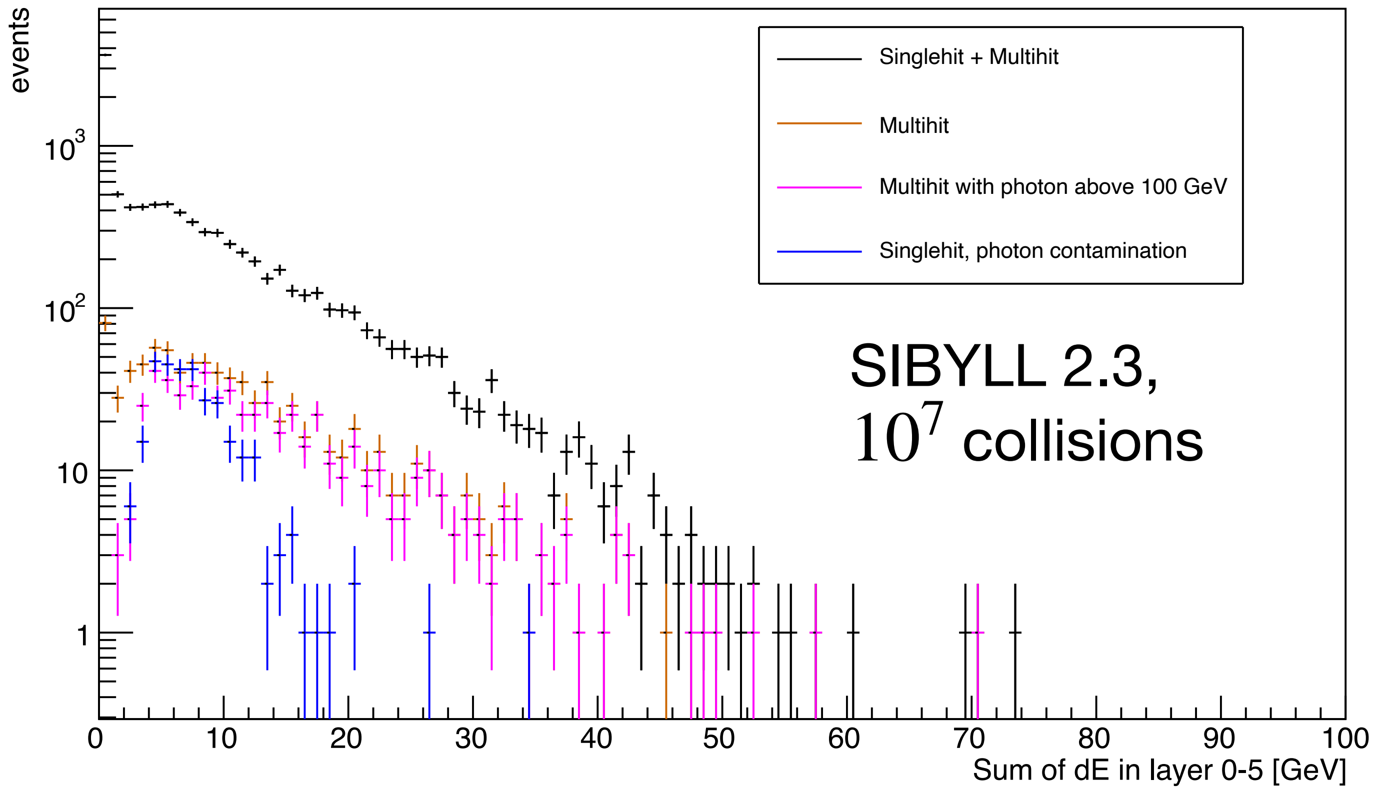
Multi-hit enhanced/reduced samples

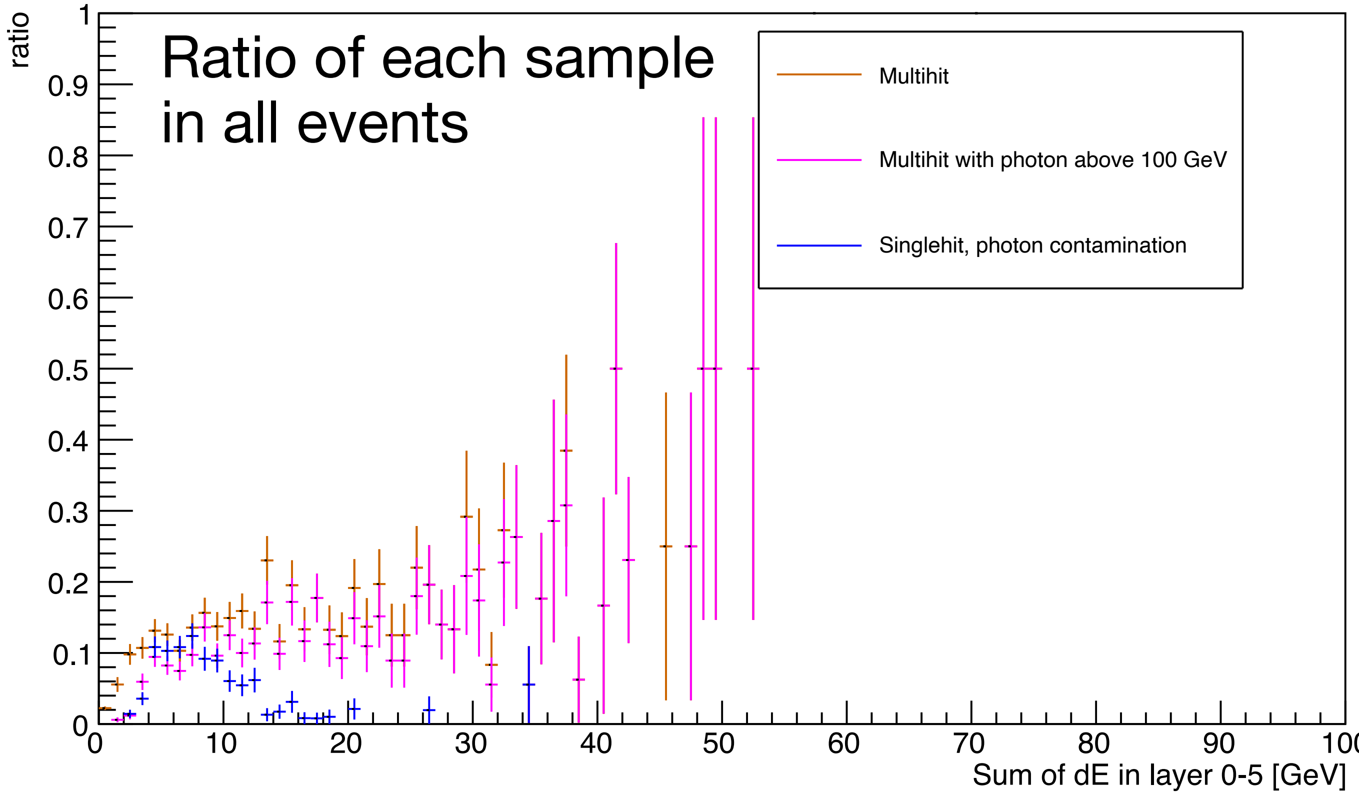
Sum of energy deposits in layer 0-5



Large tower, Region 1 (by reconstructed positions),

$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger





Black : all events

Orange : multi-hit in true level

Magenta : multi-hit, h + γ, $E_{true} > 100$ GeV for each

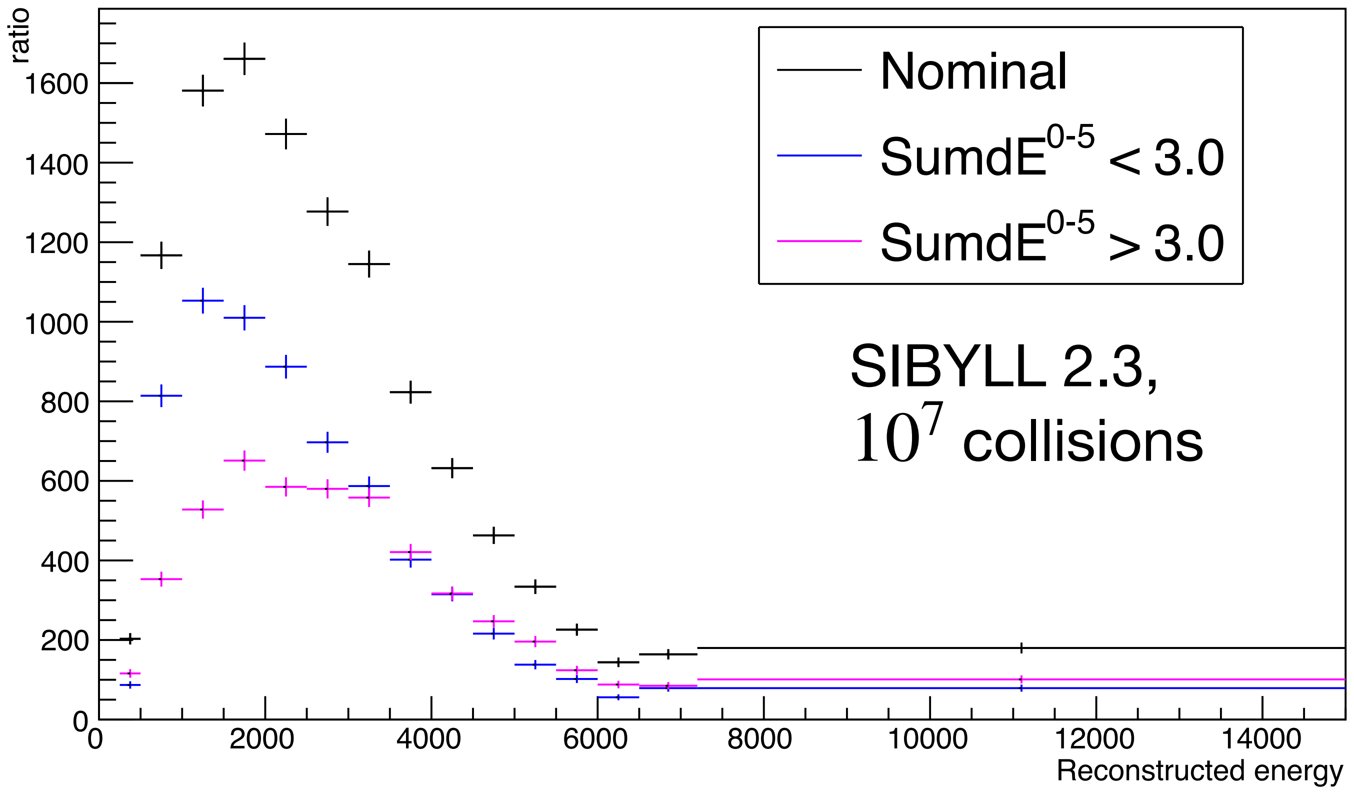
Blue : single-hit photon (contamination)

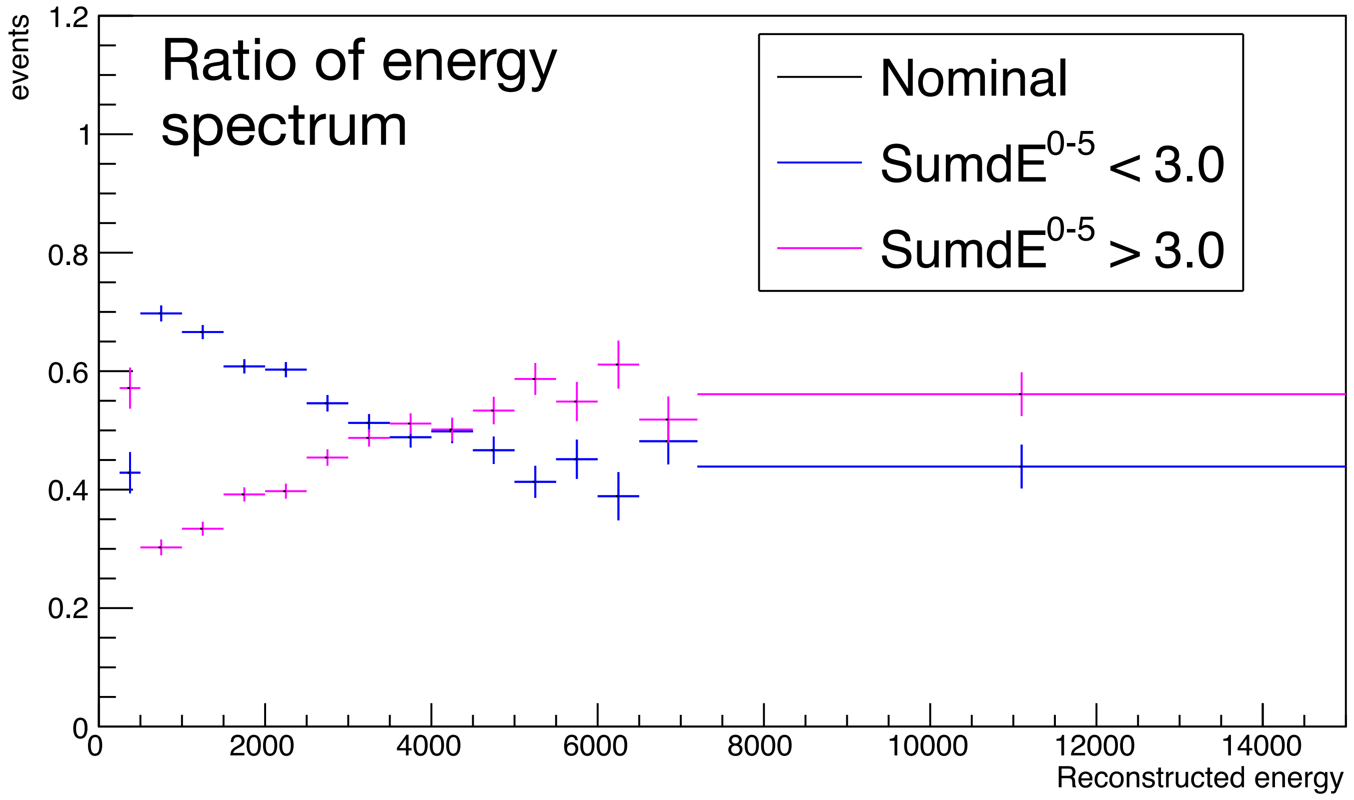
We can select the multi-hit reduced sample by selecting small energy deposits in the first 6 layers.

Energy spectrum

Multi-hit reduced / enhanced samples

Large tower, Region 1 (by reconstructed positions),
$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger





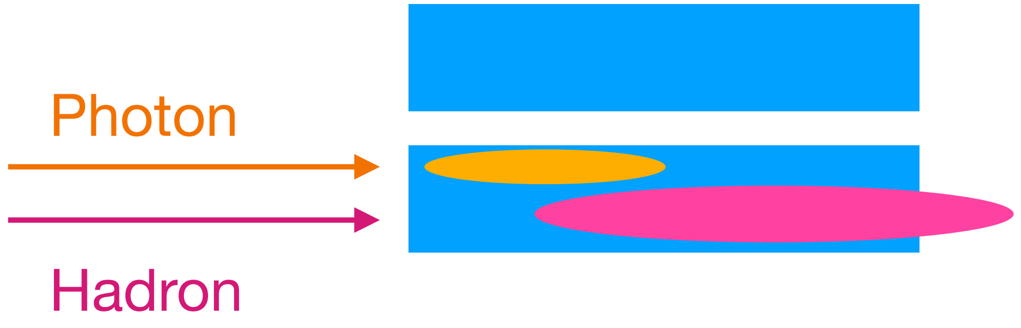
Black : all events
Blue : small energy deposits (Multi-hit reduced sample)
Magenta : large energy deposits (Multi-hit enhanced sample)

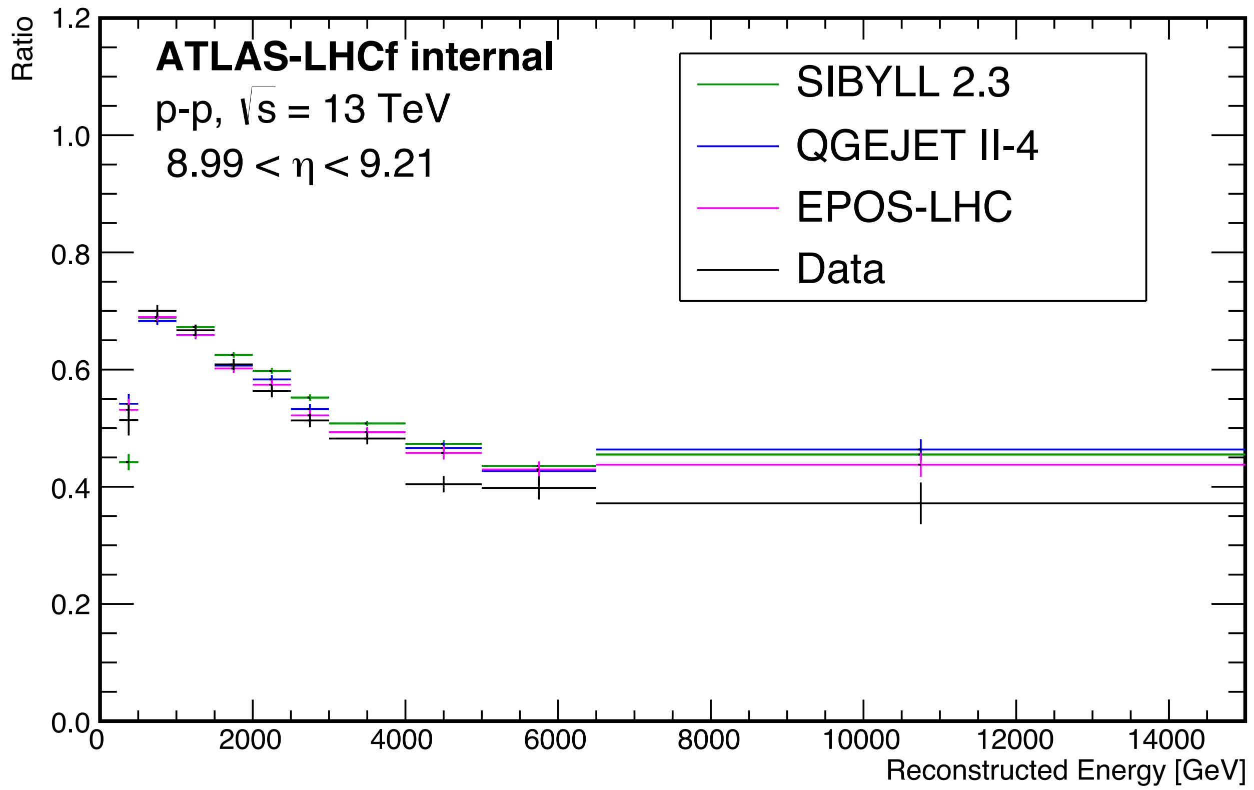
Possibility of validation!!

Ratio of energy spectrum

Ratio = (multi-hit reduced)/(nominal spectrum)

Large tower, Region 1 (by reconstructed positions),
$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger





We found differences between data and MC predictions.

=> Template fitting using two free parameters for the normalization of contamination and multi-hit events

Step 1) Get a multi-hit normalization factor γ for the multi-hit corrections using the template fitting.

Step 2) Apply the factor γ and its error to the multi-hit predictions and get modified multi-hit corrections and its error.

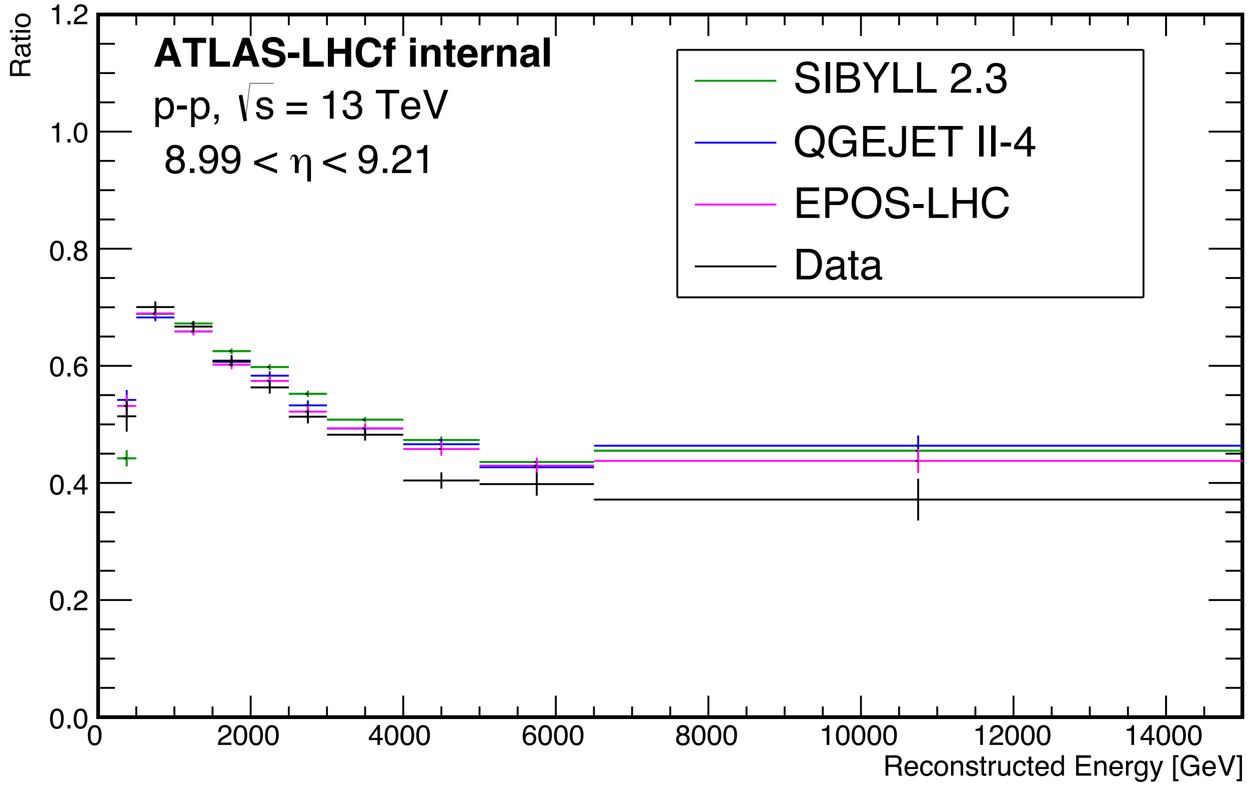
$$C^{\mathrm{MH}} = \frac{N^{\mathrm{MH\ ideal}} + N^{\mathrm{SH}}}{N^{\mathrm{MH\ obsreved}} + N^{\mathrm{SH}}}$$ (correction before tuning)

=> $$C^{\mathrm{MH}} = \frac{\gamma N^{\mathrm{MH\ ideal}} + N^{\mathrm{SH}}}{\gamma N^{\mathrm{MH\ obsreved}} + N^{\mathrm{SH}}}$$ (correction after tuning)

Template fitting

Ratio of multi-hit reduced to inclusive

Large tower, Region 1 (by reconstructed positions),
$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger



Minimizing the following value

$$\sum \frac{(R^{\mathrm{data}} - R^{\mathrm{MC}})^2}{\sigma^{R^{\mathrm{data}}} + \sigma^{R^{\mathrm{MC}}}}$$

$$R^{MC} = \frac{\alpha N_{\mathrm{cut}}^{\mathrm{single-photon}} + \beta N_{\mathrm{cut}}^{\mathrm{single-hadron}} + \gamma N_{\mathrm{cut}}^{\mathrm{multihit}}}{\alpha N^{\mathrm{single-photon}} + \beta N^{\mathrm{single-hadron}} + \gamma N^{\mathrm{multihit}}}$$

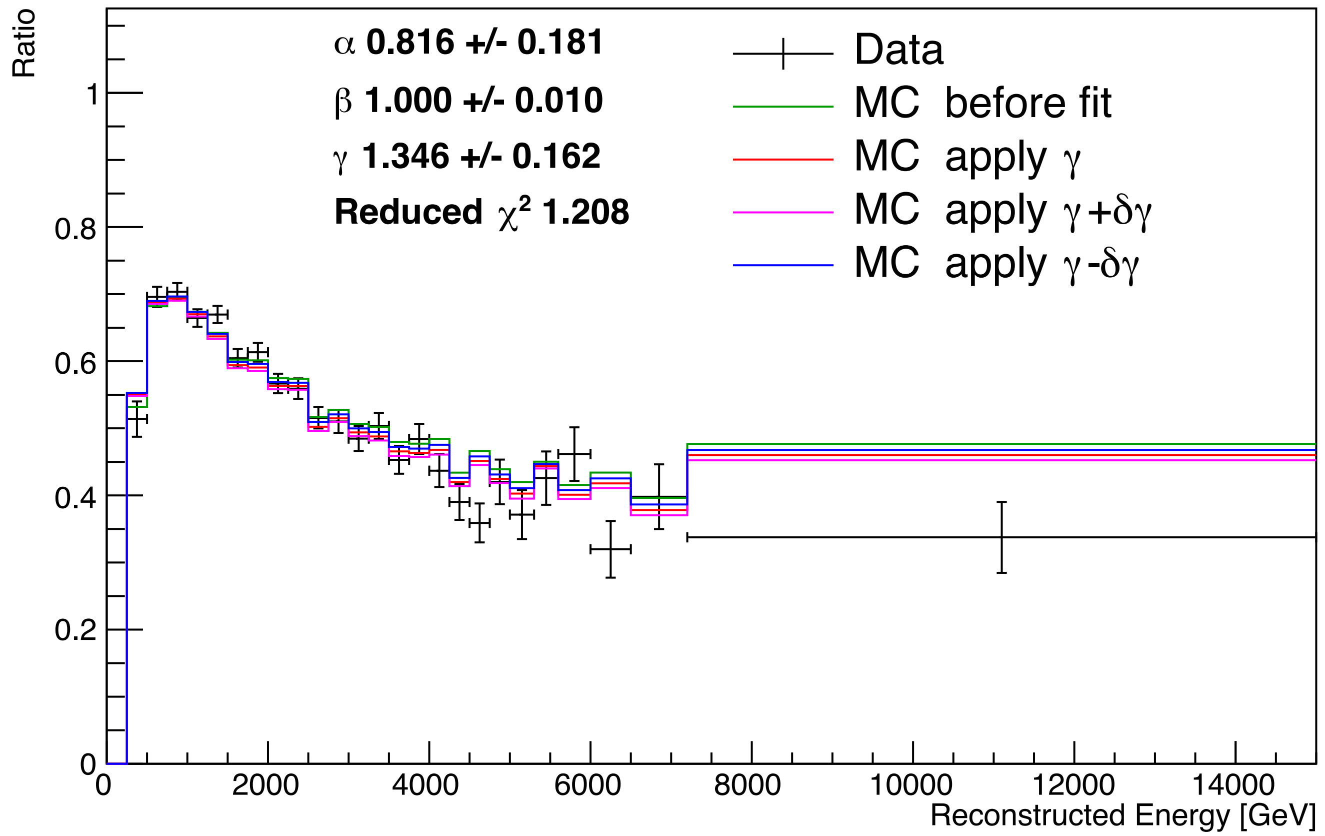
Parameter β is fixed to 1.0

Template fitting using EPOS-LHC

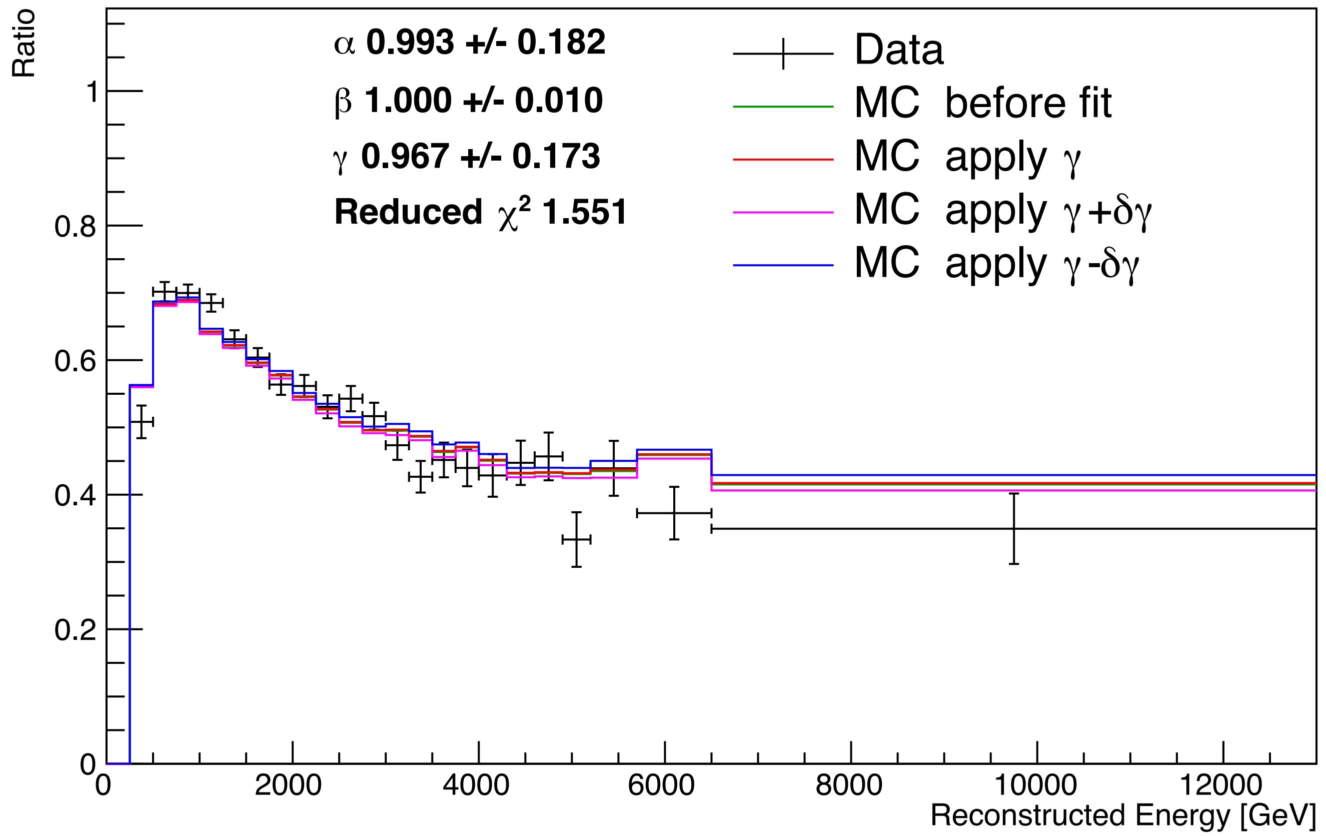
Ratio of multi-hit reduced to inclusive

Large tower, Region 1 and 2 (by reconstructed positions),
$L_{2D} > 25.$, $E_{rec} > 250$ GeV, passed software trigger

Region 1



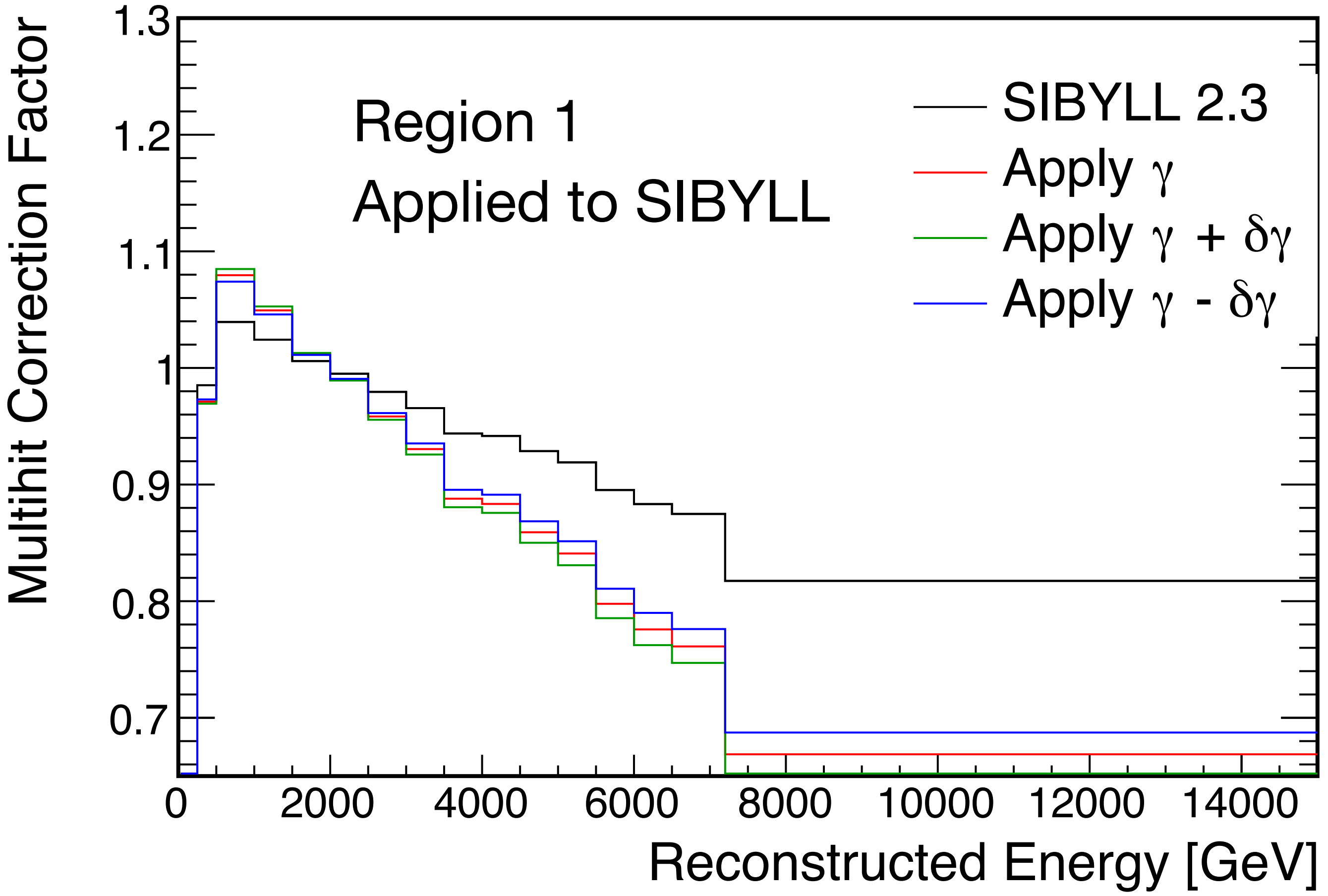
Region 2

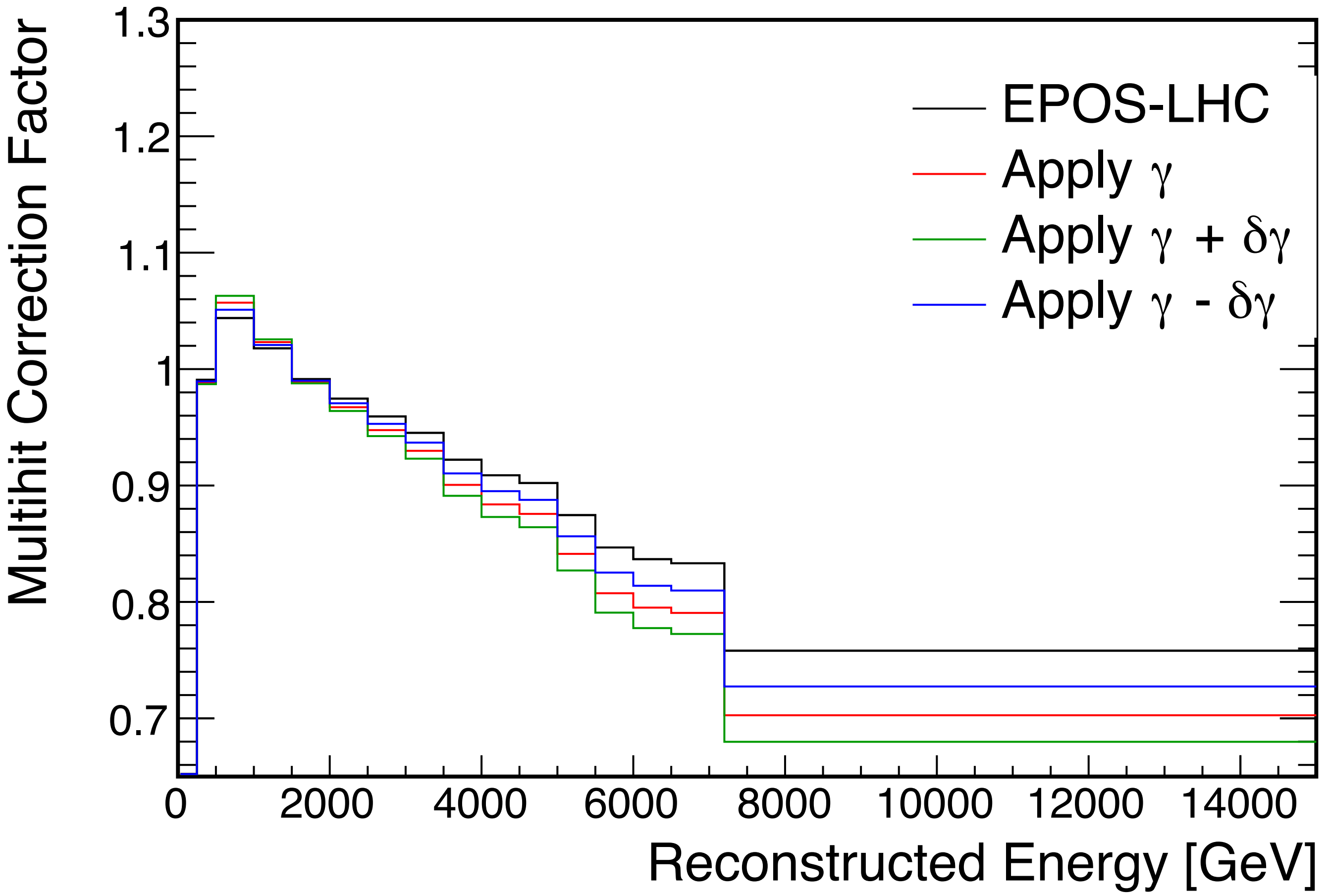


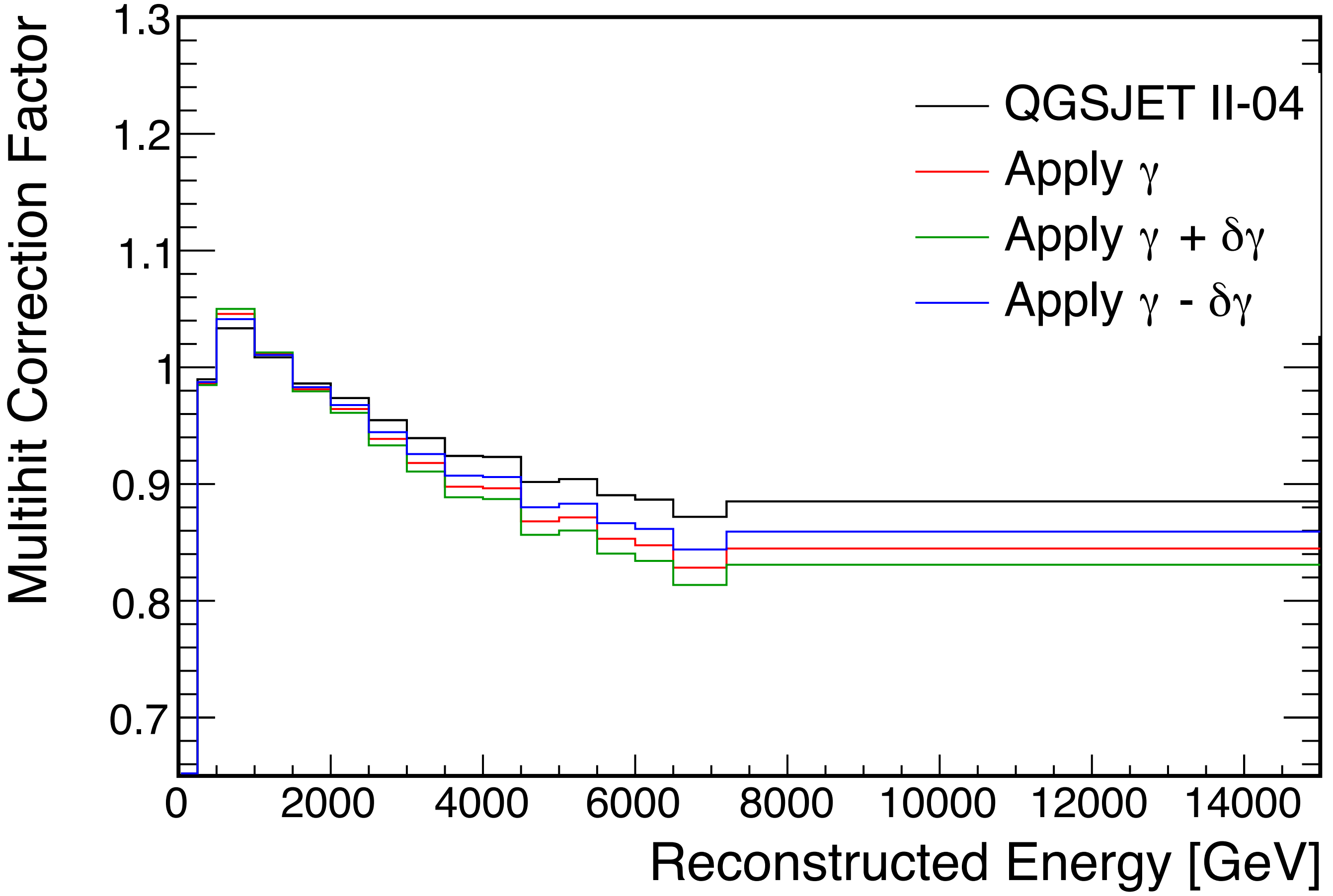
Apply data-driven factors

Multi-hit correction for $10 \leq N_{\text{track}} < 16$

The data-driven factor was applied.





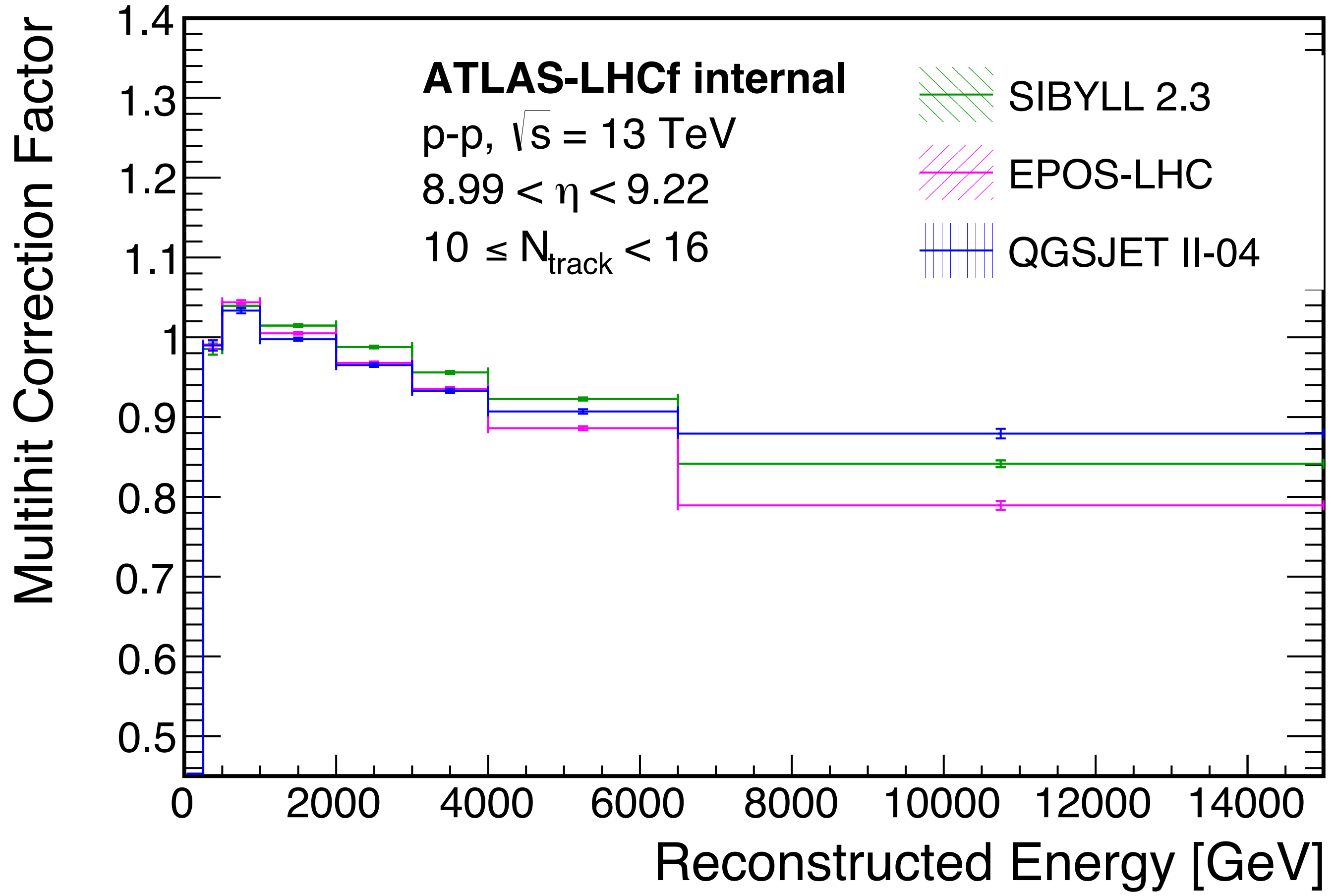


Apply data-driven factors

Multi-hit correction after applying the data-driven normalization factor

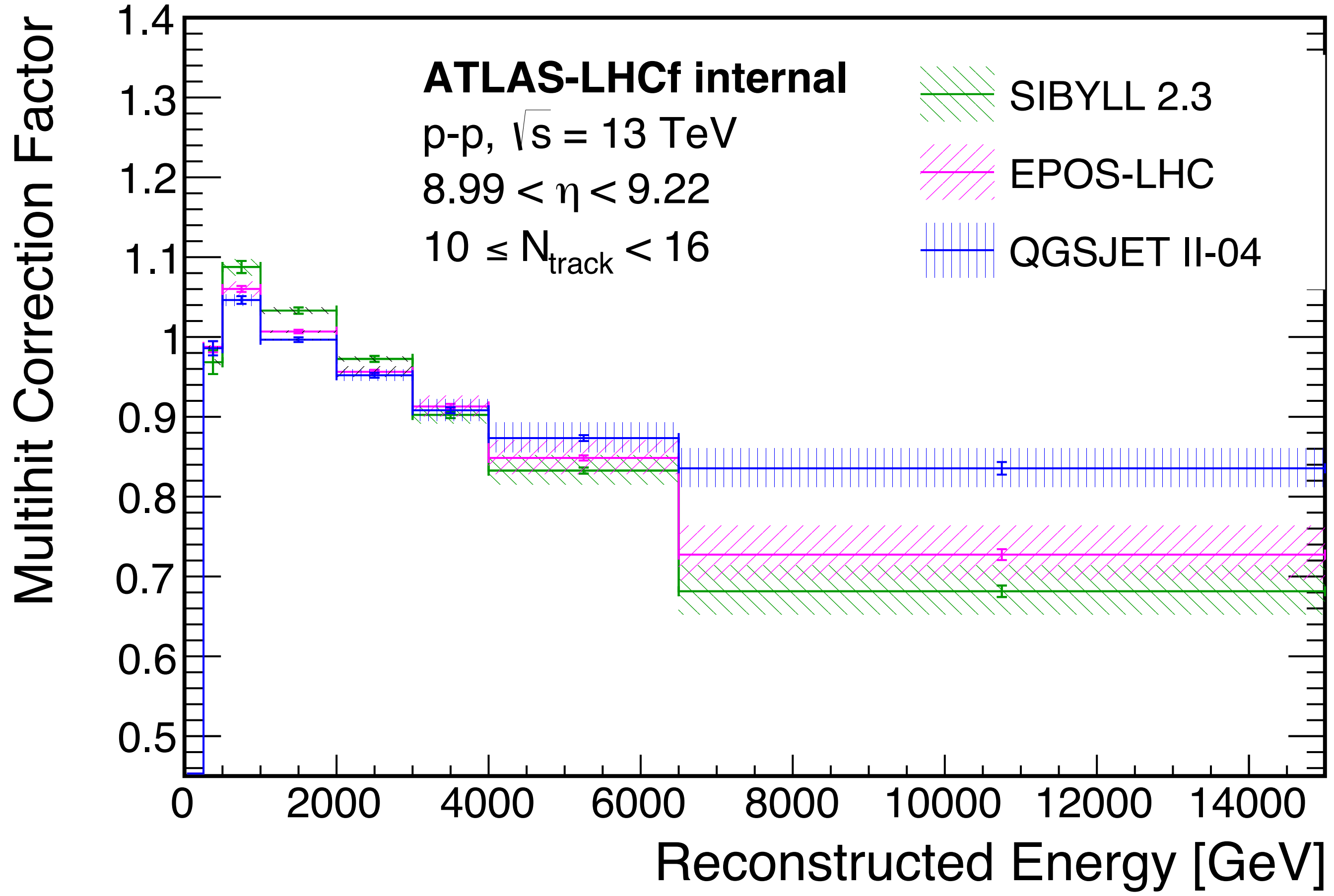
Region 1

No factor applied



Hatched regions: considering errors in factors

Error bar: statistical errors of MC.

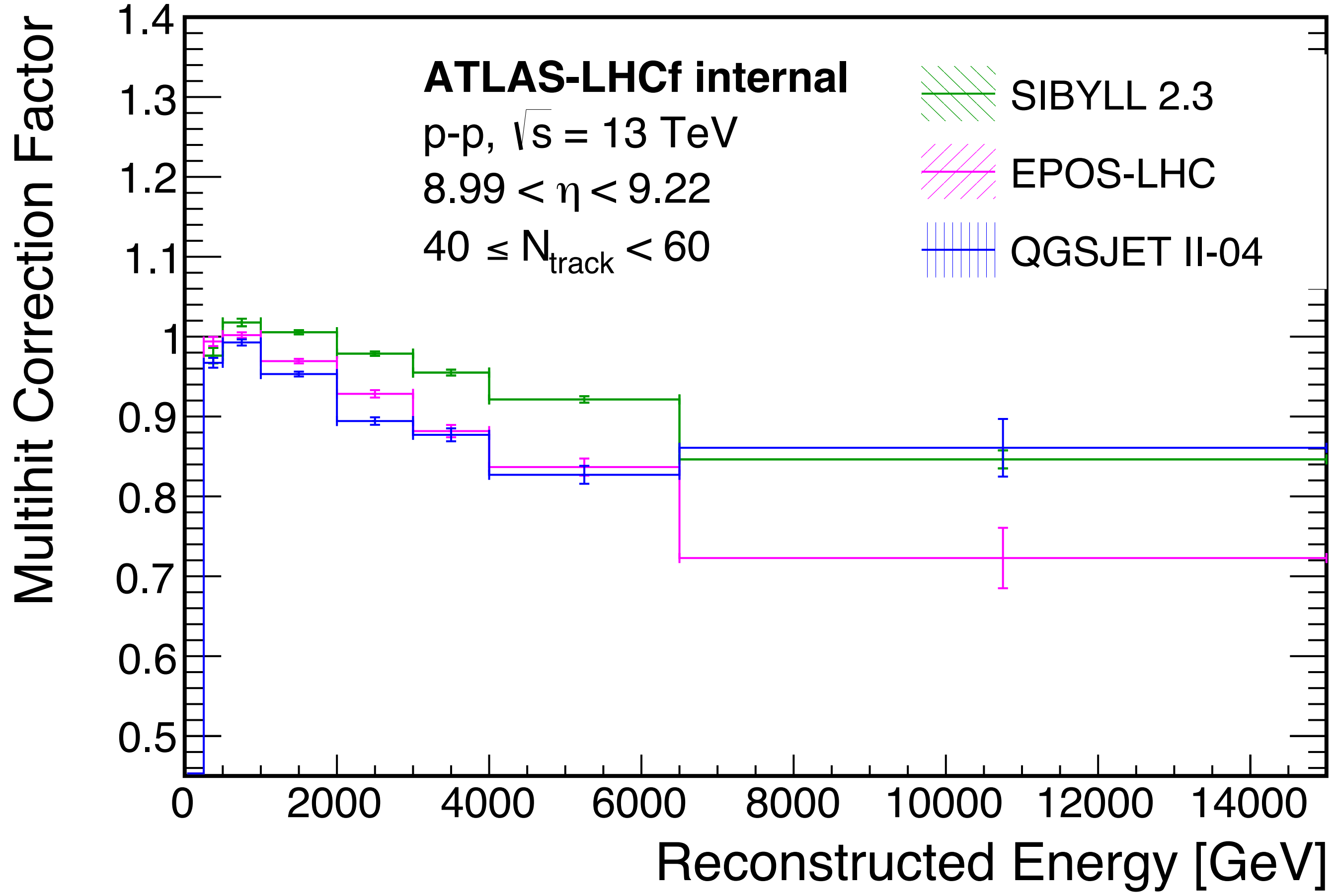


Apply data-driven factors

Multi-hit correction after applying the data-driven normalization factor

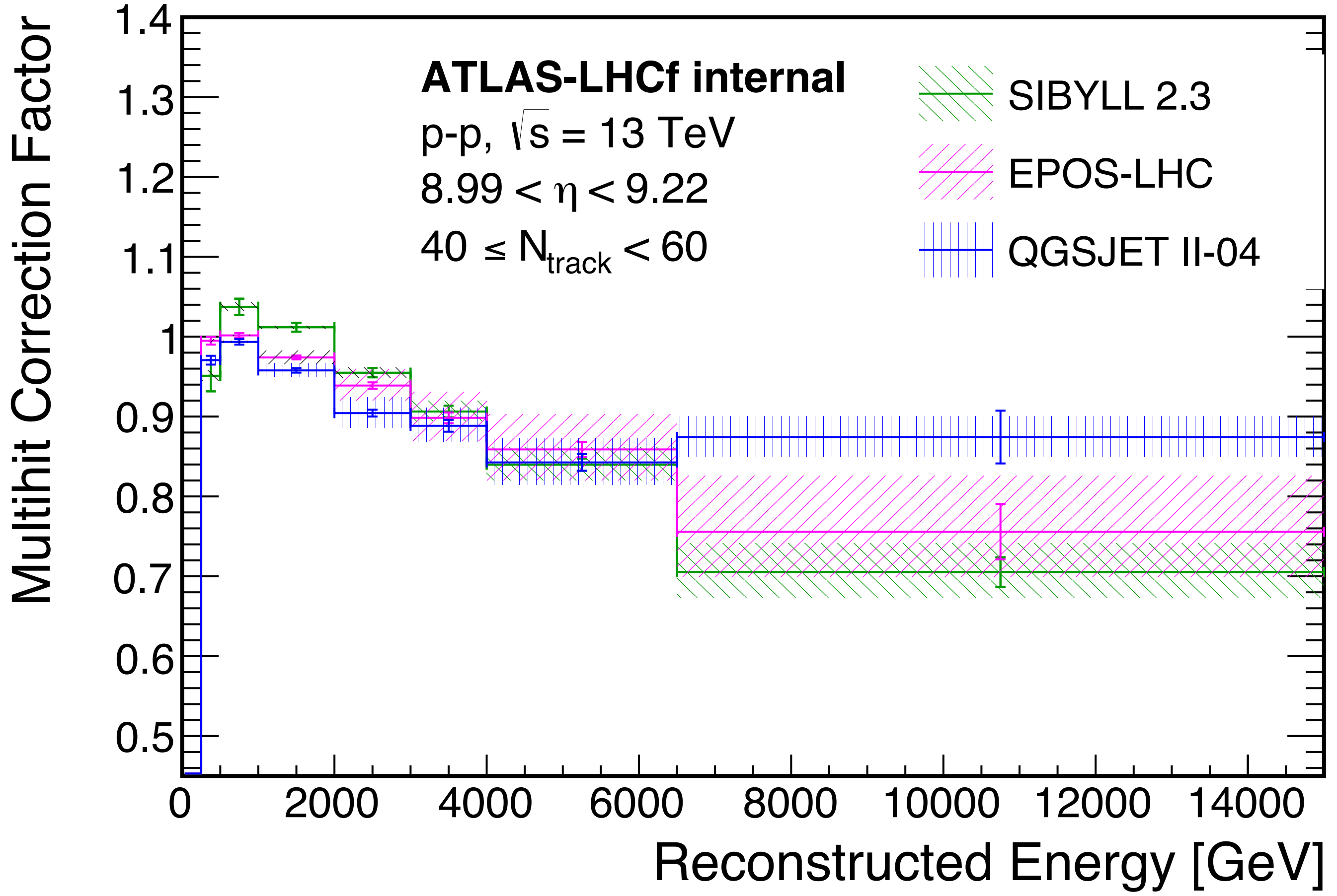
Region 1

No factor applied



Hatched regions: considering errors in factors

Error bar: statistical errors of MC.



Multi-hit corrections

MC-driven correction factors with the data-driven normalization factor

- Multi-hit enhanced/reduced samples were selected using the first several layers of the LHCf detector
- MC validation using Multi-hit reduced samples
  - The sum of energy deposits in the first 6 layers works well to reduce multi-hit events.
  - Validation of hadronic interaction models using the multi-hit reduced sample was performed.
  - Differences between data and MC.
- Template fitting using two free parameters for normalization of single-photon contaminations and multi-hit contributions.
  - Note that single-photon contaminations is quite small.
- The data-driven normalization factor for multi-hit contributions was applied to MC predictions.
  - Then, we got MC-driven correction factors with the tuning of MC.

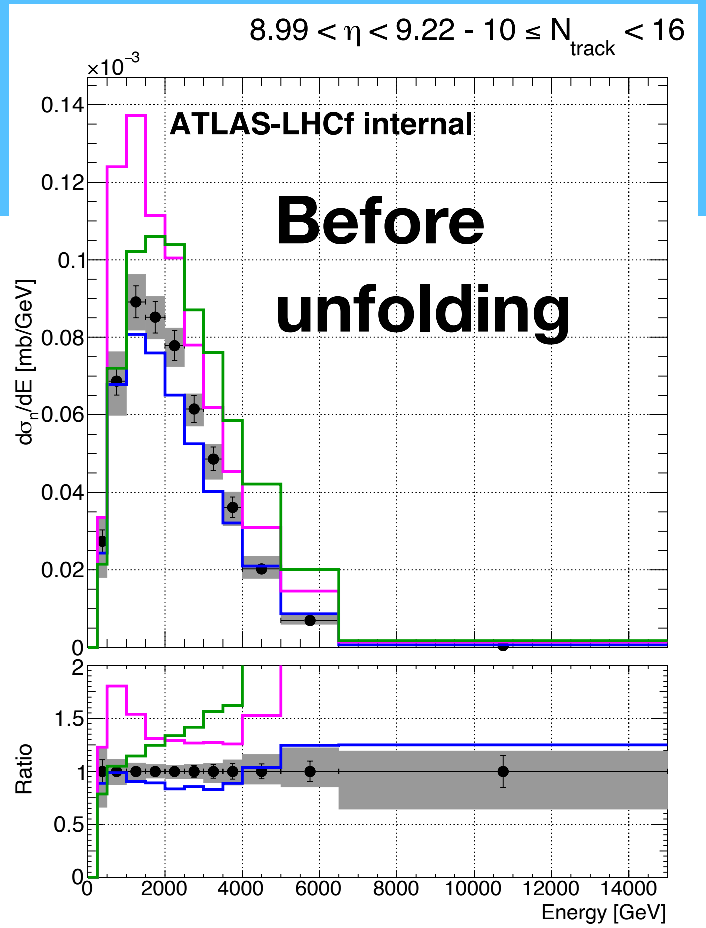
Unfolding

Two dimensional unfolding

Extend the method for LHCf-Arm2 analysis

- Strategy
    - Two dimensional unfolding using RooUnfold package
        - Iterative baysan method
    - Extend the method for LHCf-Arm2 analysis
        - LHCf-Arm2 analysis : https://doi.org/10.1007/JHEP11(2018)073
    - Two dimensional histograms for inputs/outputs
        - E_{rec} and N_{track} for input / E_{true} and N_{charged} for output
    - Response matrix
        - 1D response from ATLAS full simulation & 1D response from LHCf full simulation
            - Assumption : detector response of ATLAS and LHCf detector are independent
- Update
    - Performance test of unfolding
    - Systematic uncertainty
    - Candidate of final plots
- Remaining works
    - Systematic uncertainty due to unfolding

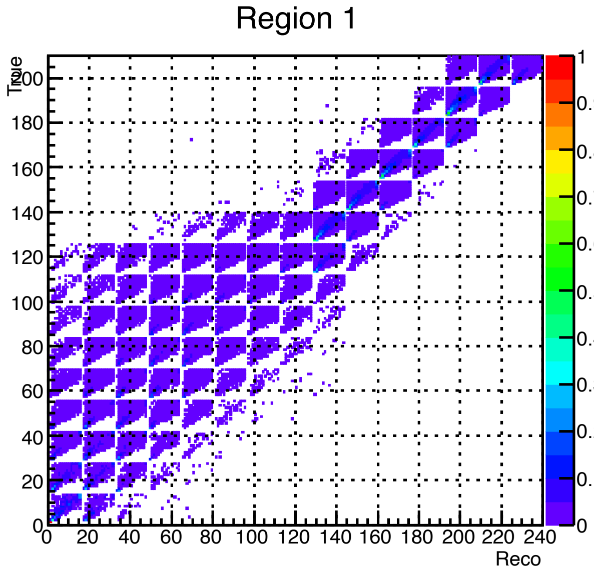
Response matrix

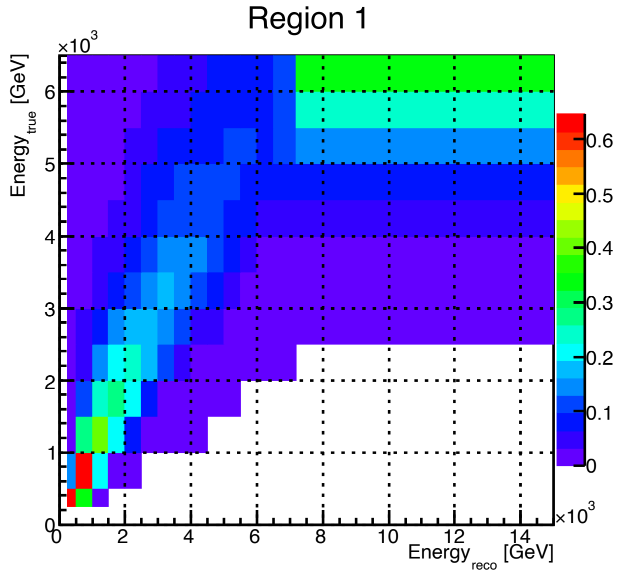


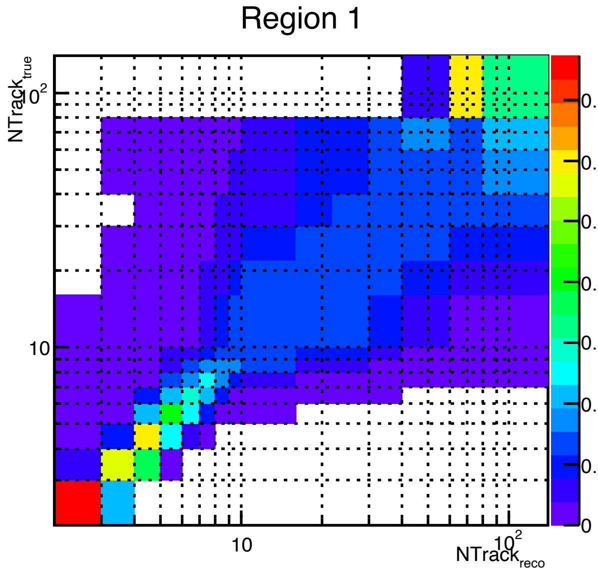
MC sample

ATLAS full simulation / LHCf full simulation

Response Matrix







Update from the last report :

Performance test of the unfolding method using the ATLAS-LHCf full MC. Then, the systematic uncertainty was estimated.

Unfolded spectrum

Two dimensional unfolded spectrum

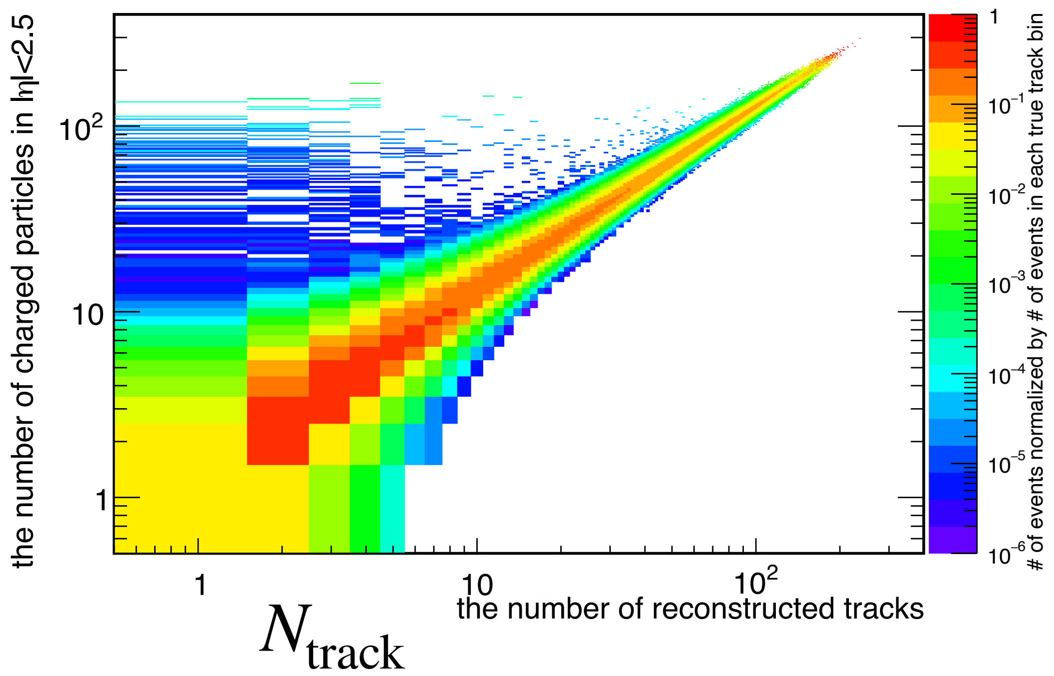
↓

Projection to each axis

Ratio of spectrum after projection

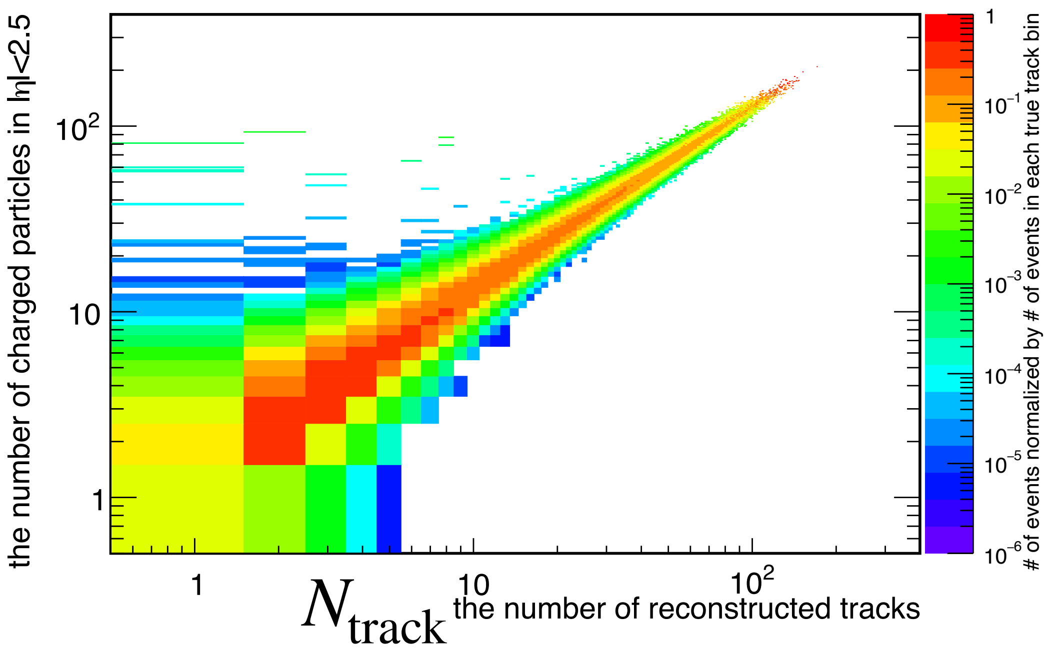
Response matrix for ATLAS tracks

PYTHIA ND

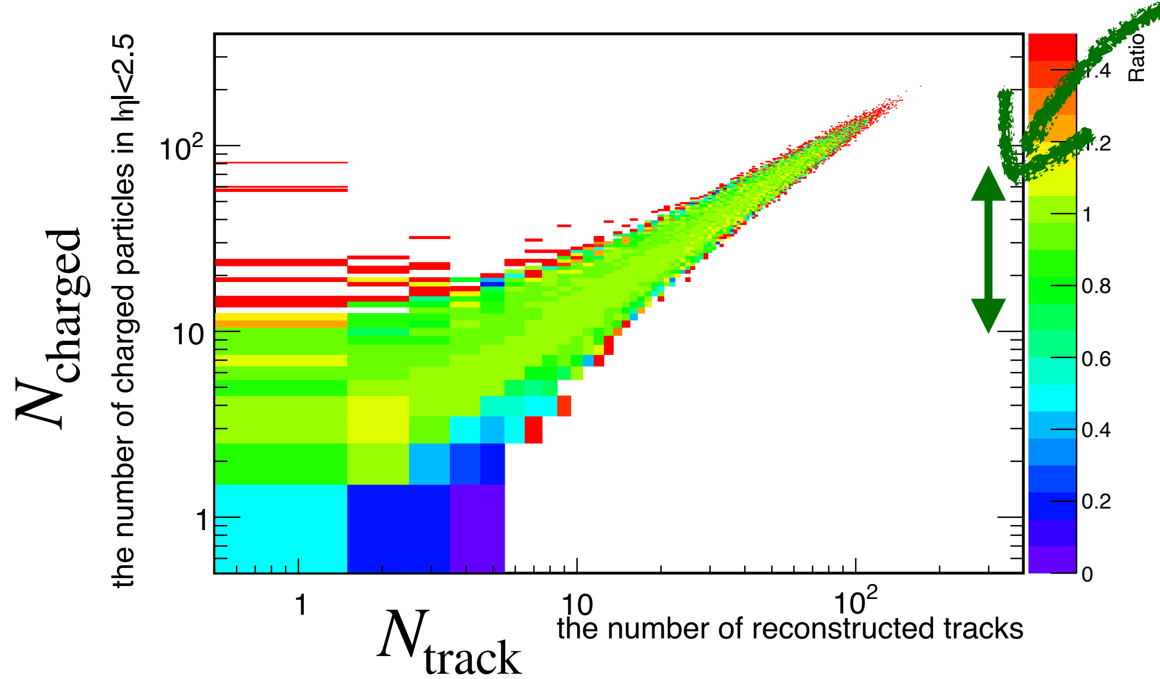


The number of events, normalized by total number of events in each $N_{charged}$ bin

PYTHIA SD



The number of events, normalized by total number of events in each $N_{charged}$ bin



Ratio of PYTHIA SD to PYTHIA ND

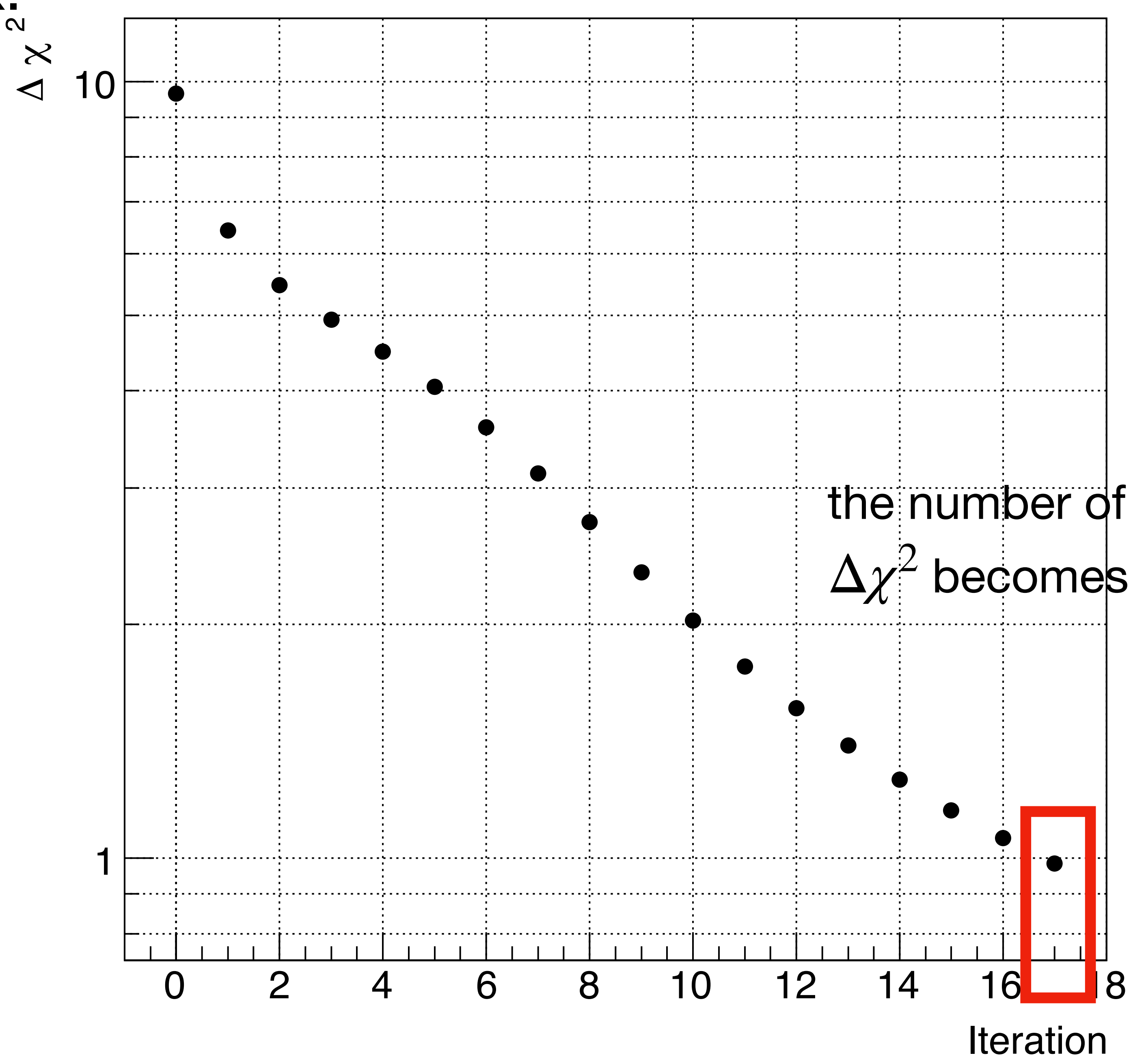
$10 \leq N_{charged} < 80$

The number of iteration

the number of iteration depends on input spectrum and the response matrix.

$\Delta\chi^2$: the χ^2 between the outputs of two consecutive iterations

Region 1



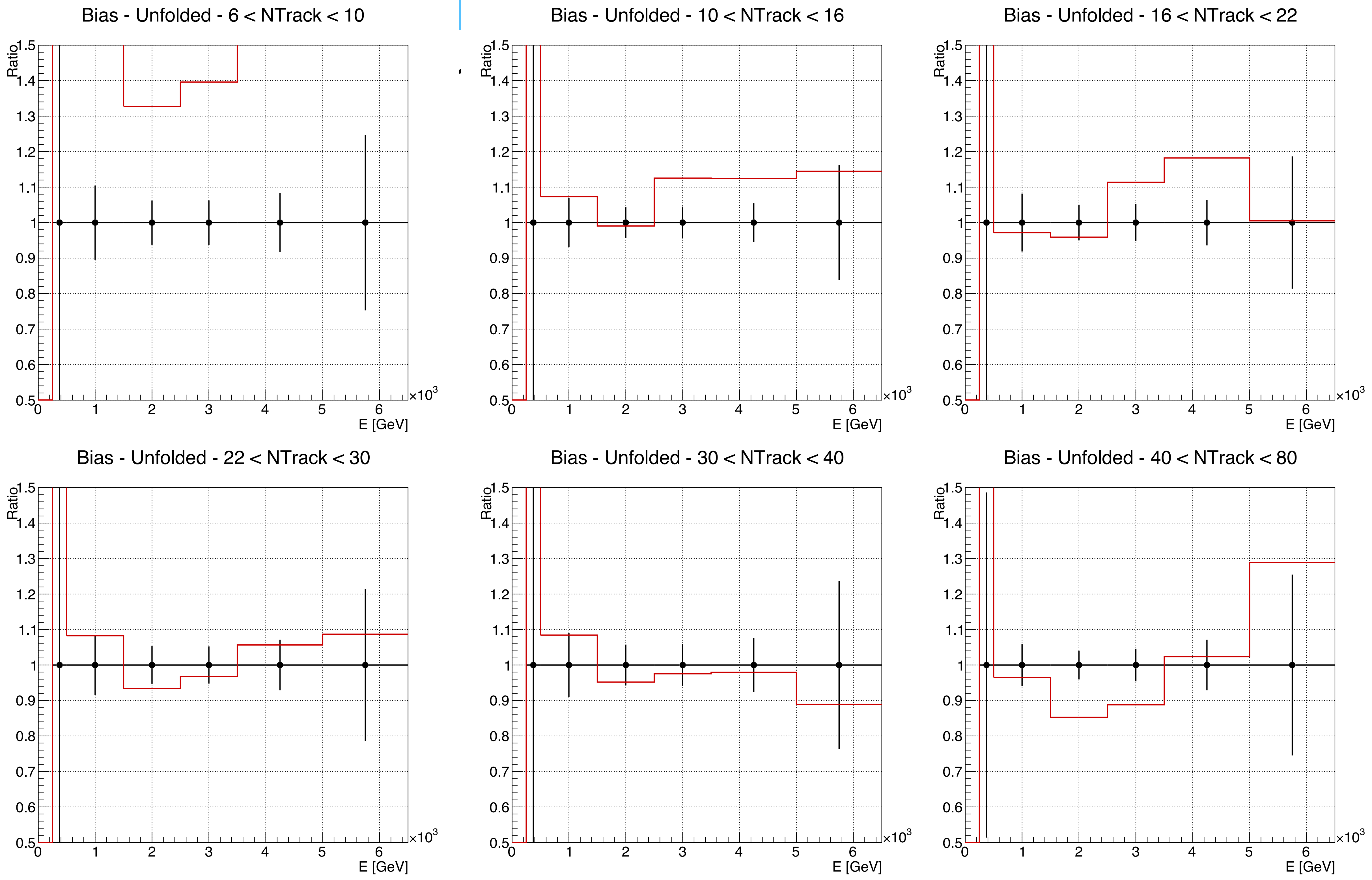
the number of iteration :
$\Delta\chi^2$ becomes less than 1

Unfolding performance

For the systematic uncertainty of the unfolding method

- Input MC sample
    - ATLAS-LHCf full MC, PYTHIA ND
- Response matrix (using two 1D matrices)
    - ATLAS full MC, PYTHIA ND
    - LHCf flat neutron sample
- Calculate bias due to unfolding from the ratio of MC truth spectrum to unfolded spectrum.

Performance test result — Region 1

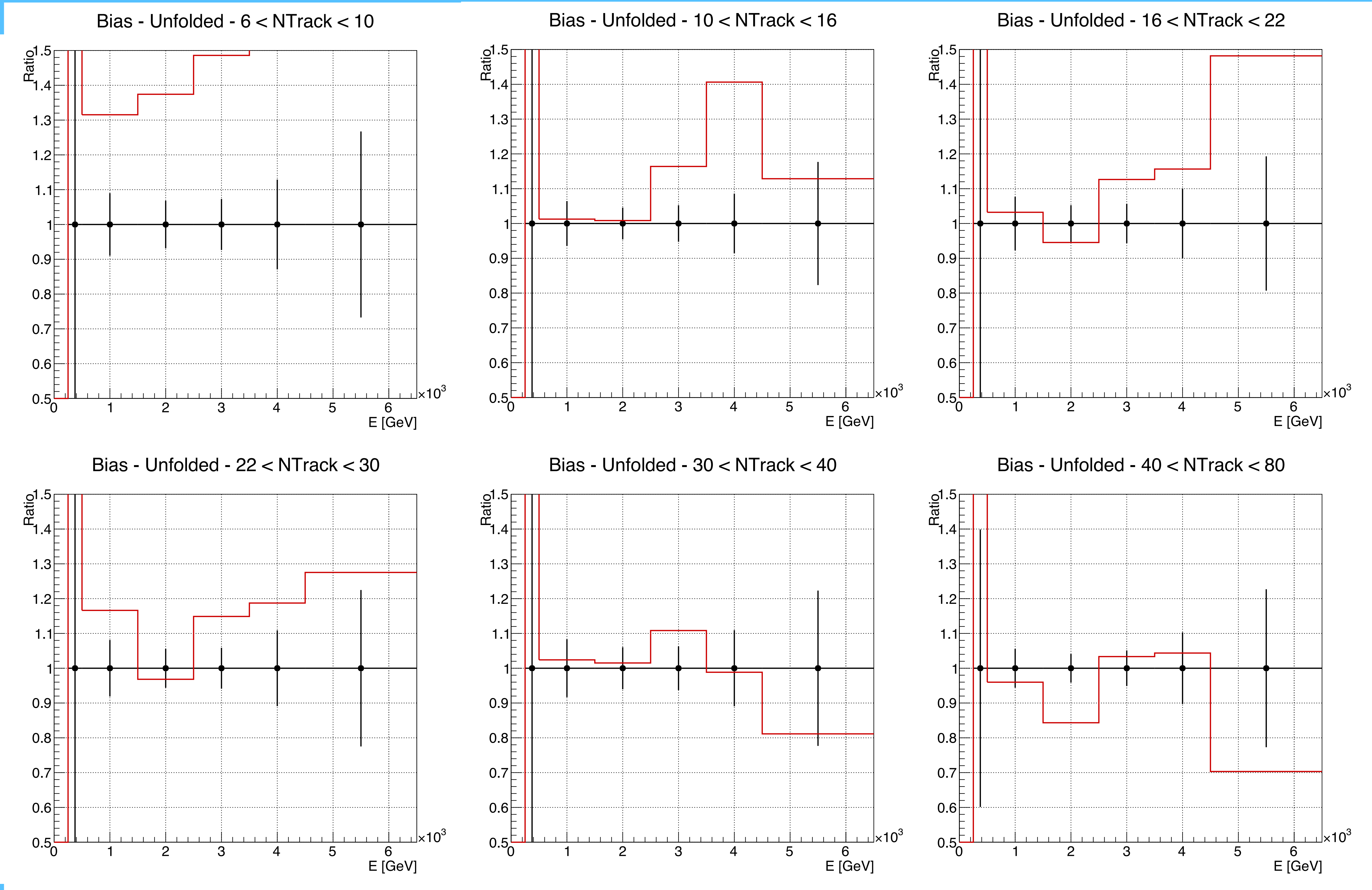


Ratio = True / Unfolded

Large bias only for

$6 \leq N_{track} < 10$

Performance test result — Region2



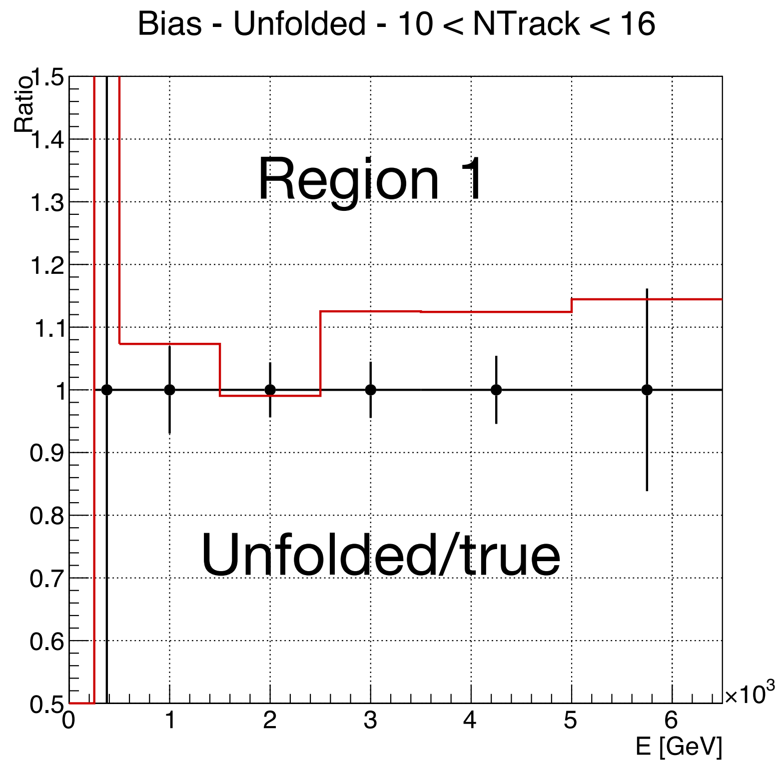
Ratio = True / Unfolded

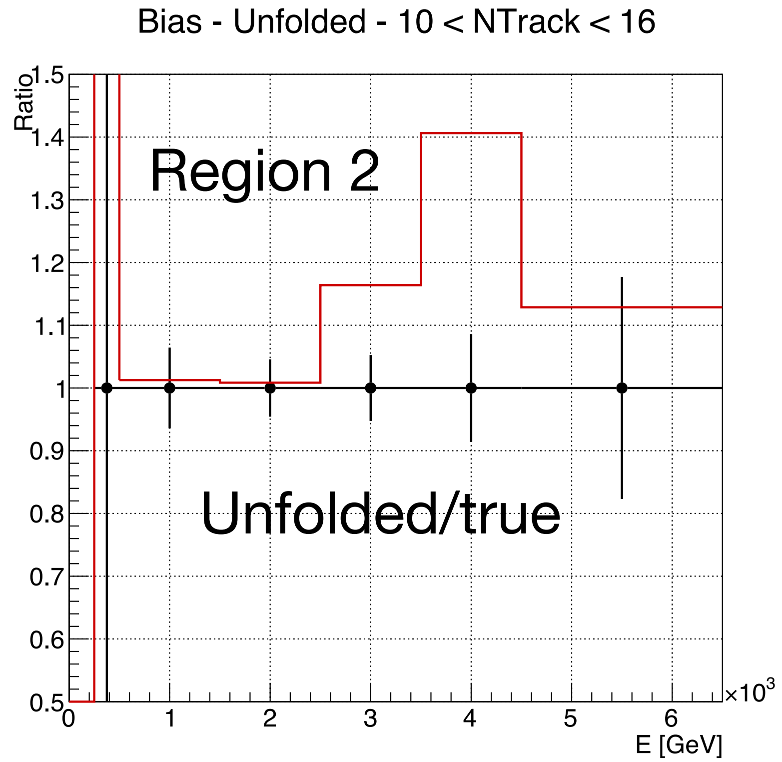
Large bias for

$6 \leq N_{track} < 10$

Larger bias than Region 1

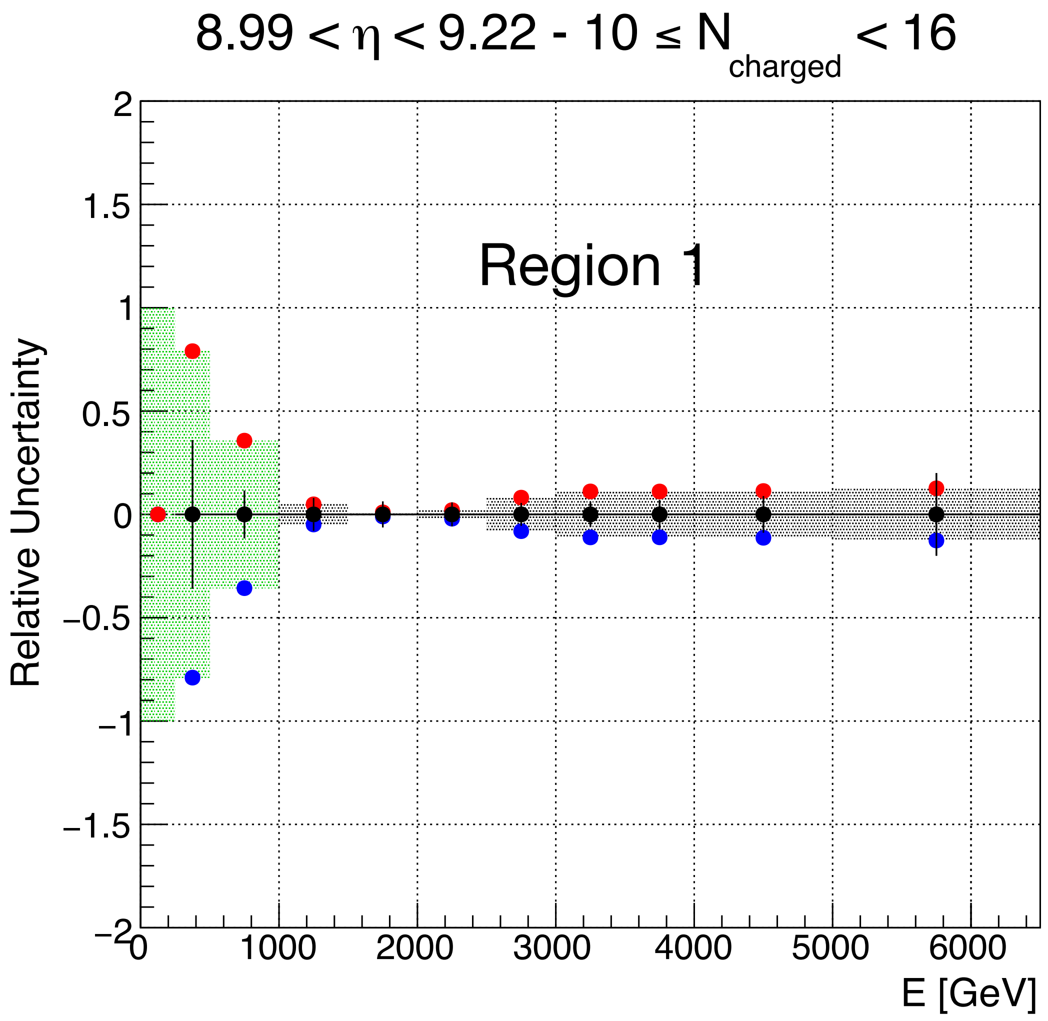
Systematic uncertainty

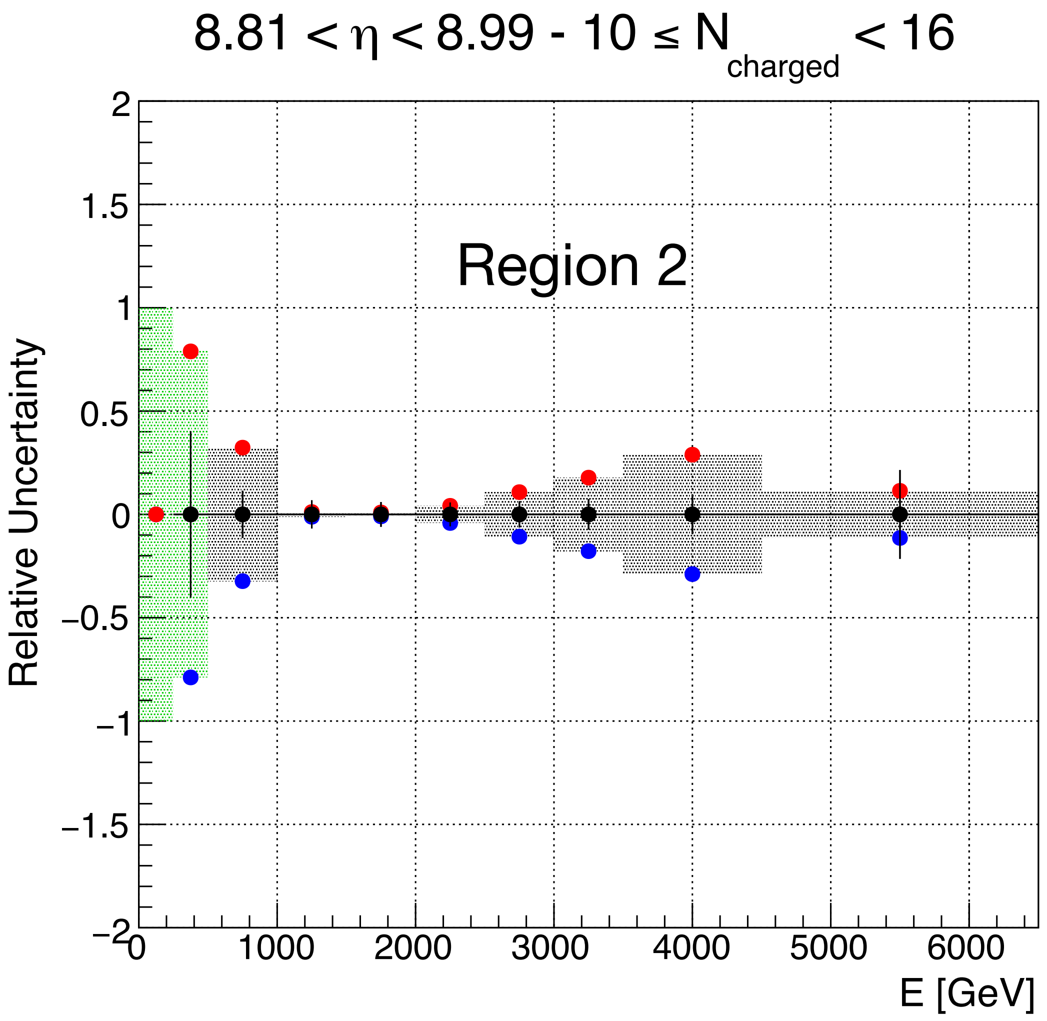




Uncertainty = true/unfolded

The size of uncertainty was used both upper and lower limits of uncertainty.



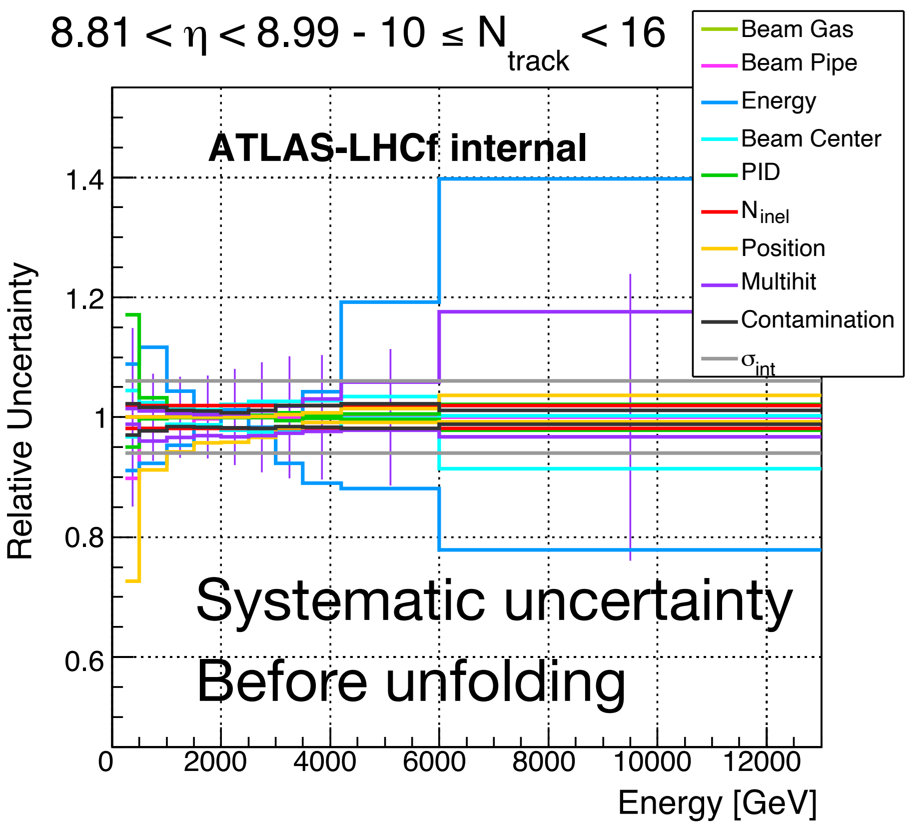


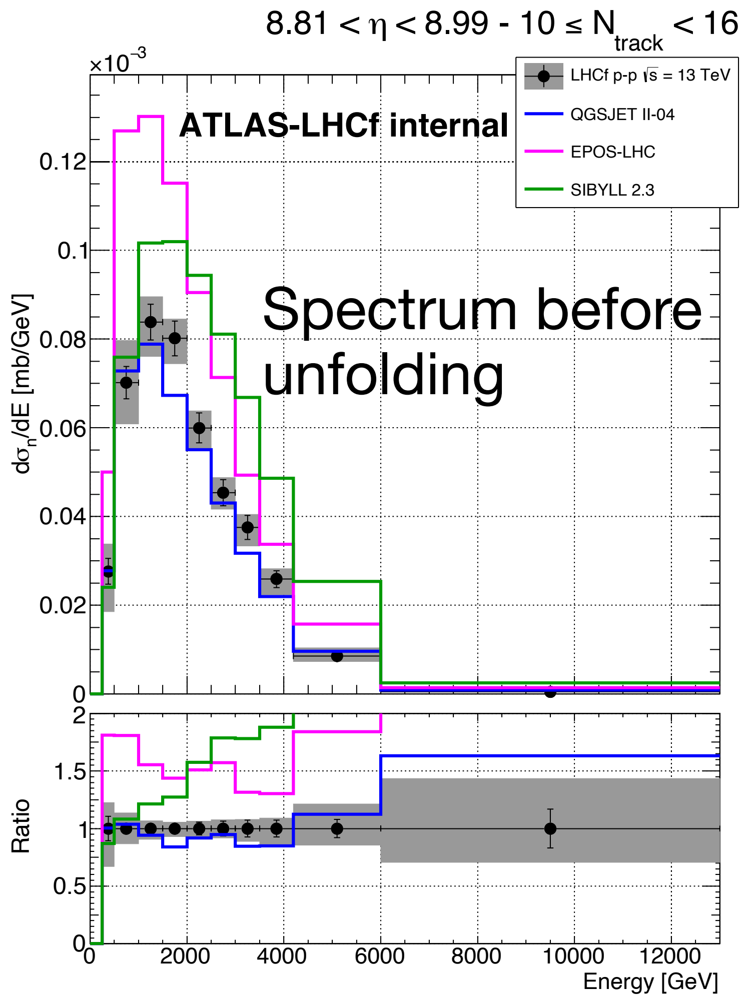
Unfolding performance

For the systematic uncertainty of the unfolding method

- Input MC sample
  - ATLAS-LHCf full MC, PYTHIA ND
- Response matrix (using two 1D matrices)
  - ATLAS full MC, PYTHIA ND
  - LHCf flat neutron sample
- Calculate bias due to unfolding from the ratio of MC truth spectrum to unfolded spectrum.
- Large bias for $6 \leq N_{\mathrm{charged}} < 10$
  - For the moment, we don't know the clear reason of this large bias.
  - In the reconstructed spectrum, we use the fine binning for $N_{\mathrm{track}} < 10$ to consider the migration correctly.
  - But it makes the number of events per bin small, and that may cause bias.
  - The wide binning in the reconstructed spectrum may cause another bias.
    - The response changes dramatically for $N_{\mathrm{track}} < 10$.

Propagation of systematic uncertainty

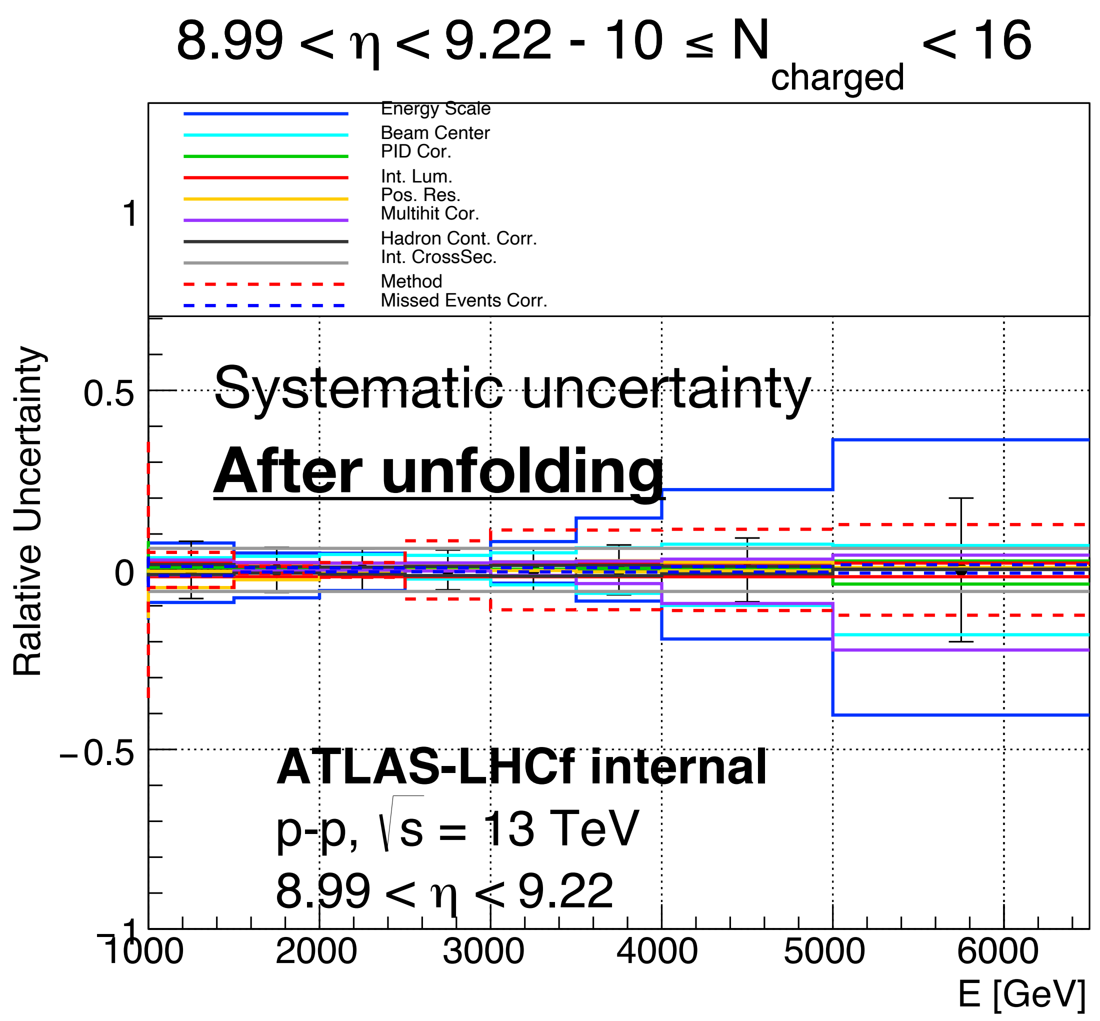




Calculations

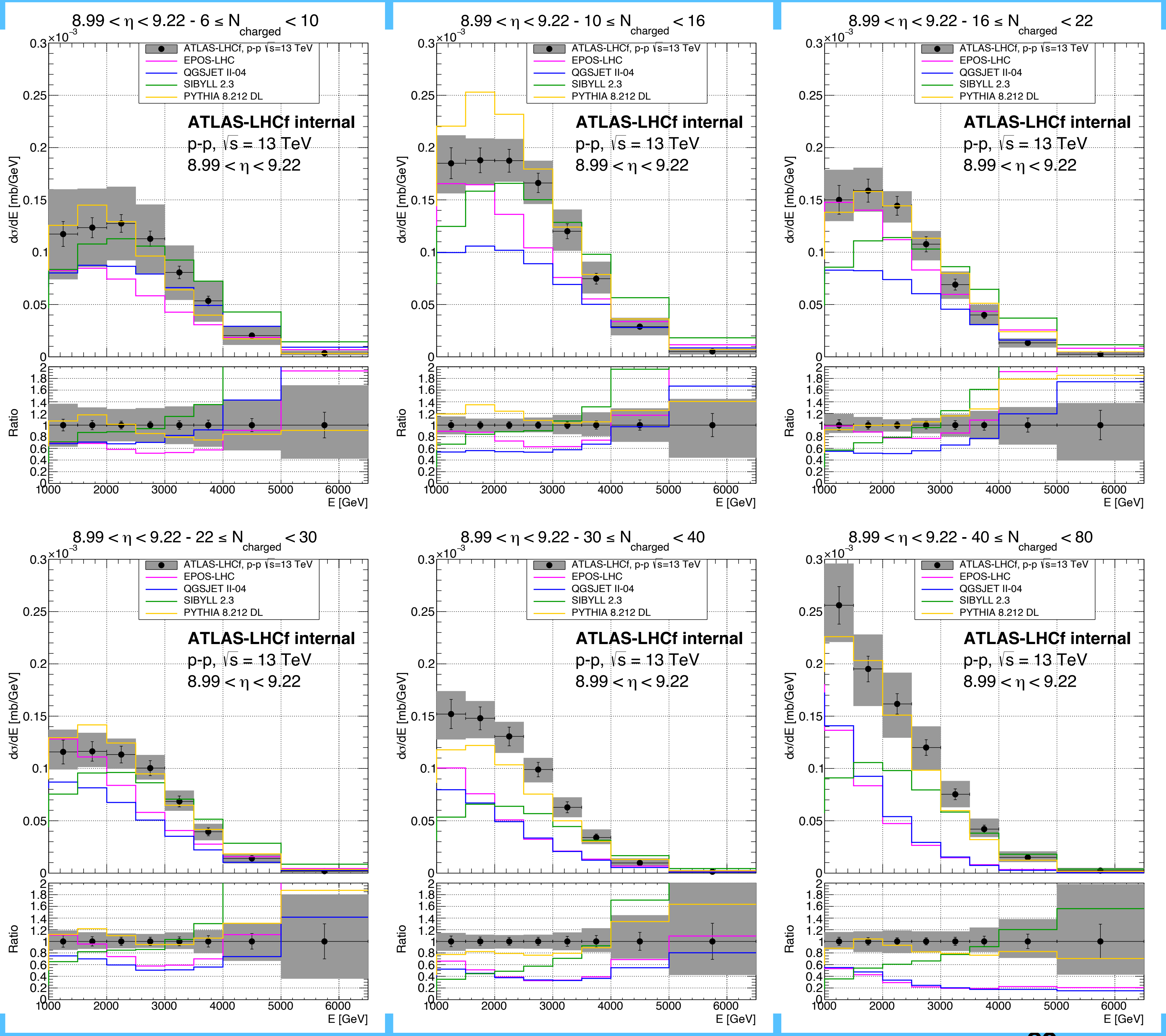
Shift spectrum before unfolding using systematic uncertainty

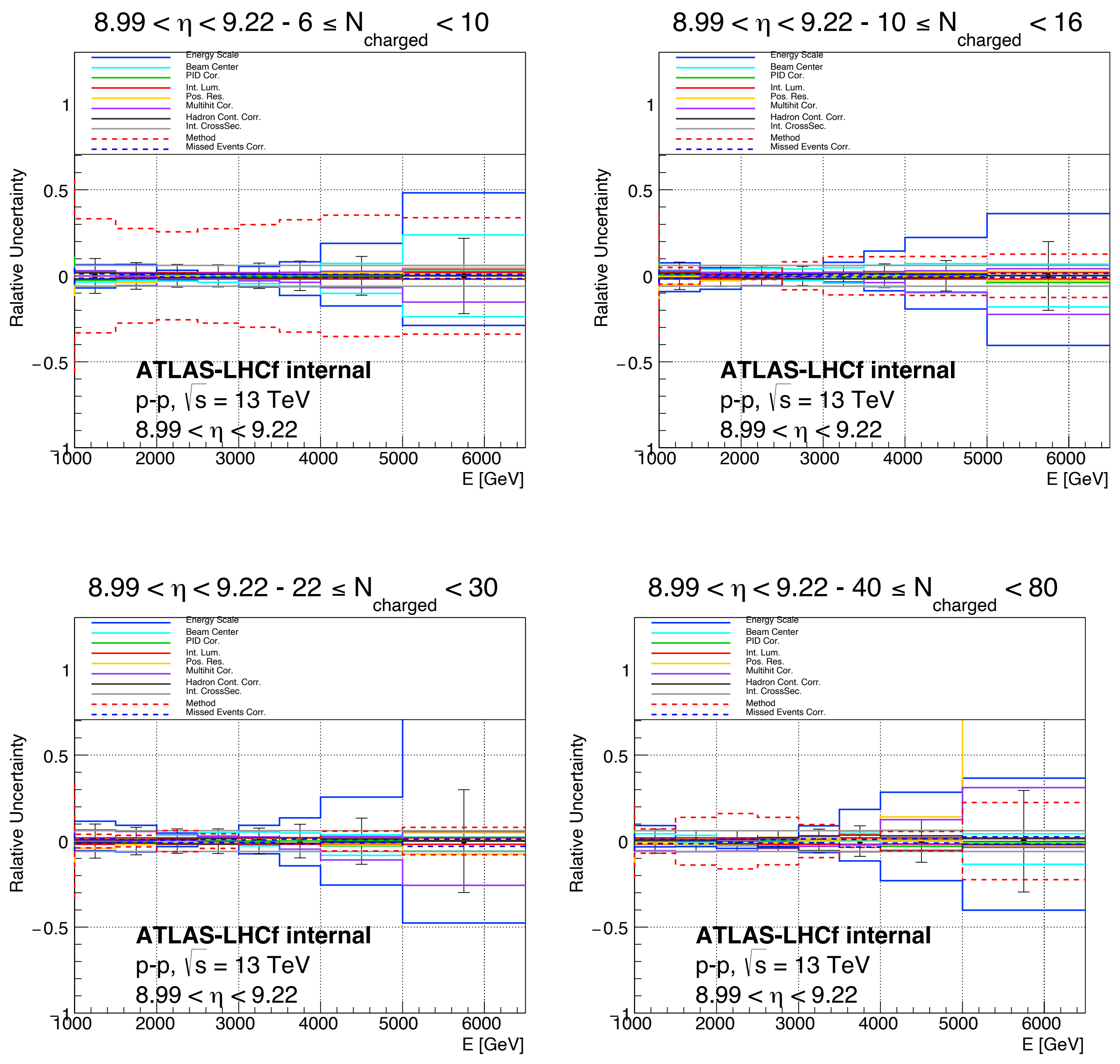
Differences after unfolding were considered as uncertainty after unfolding



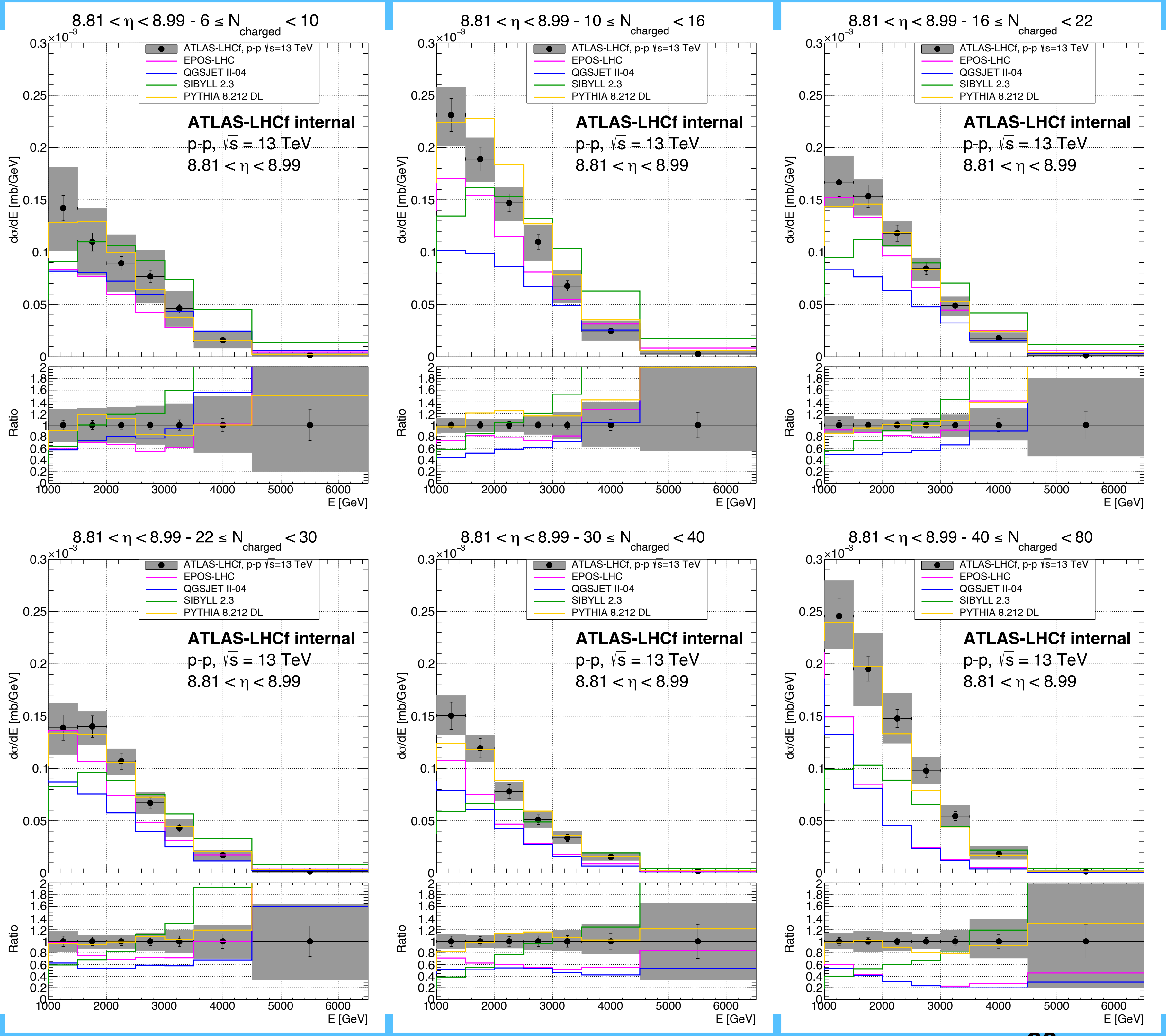
Final plots

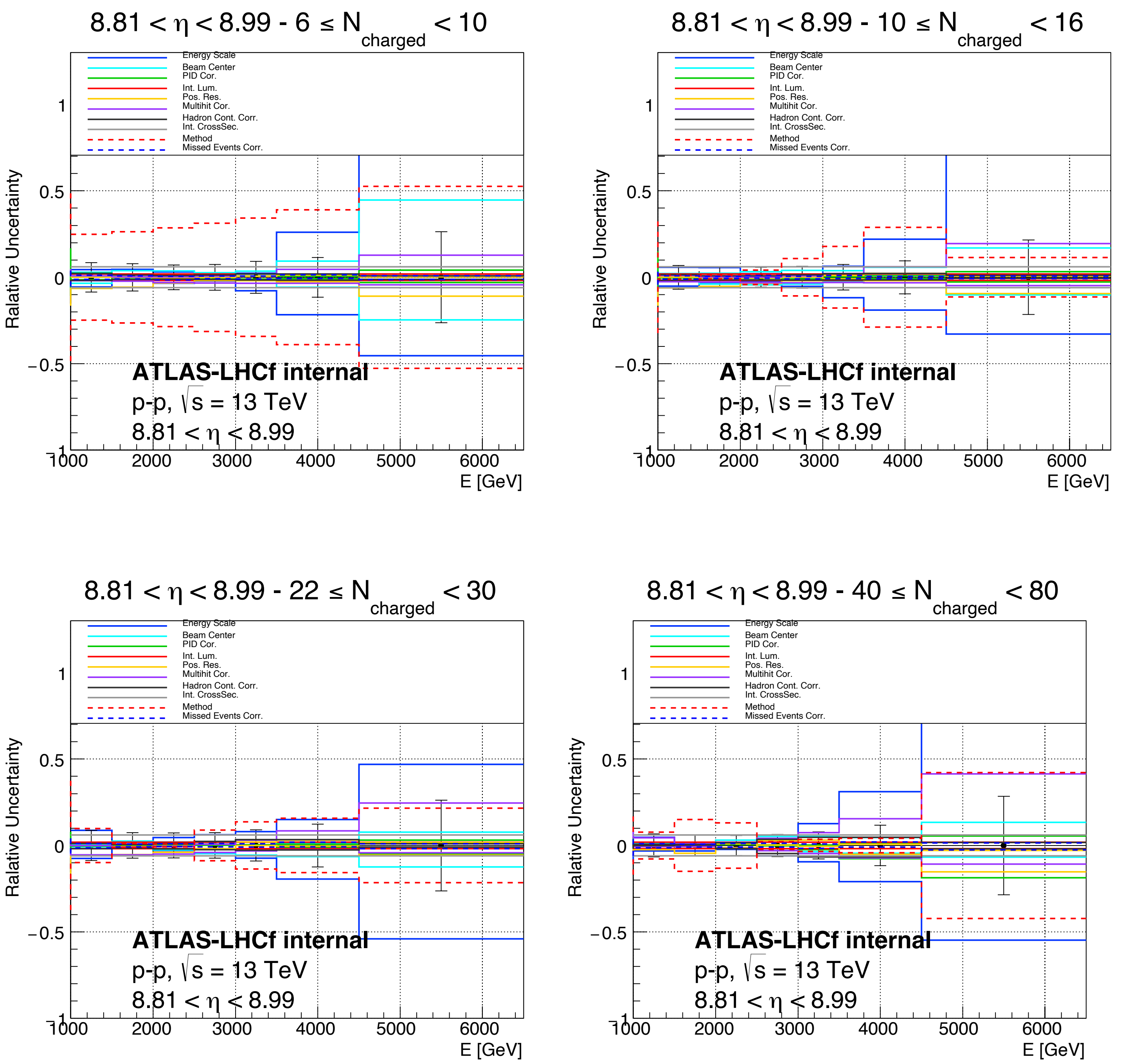
Preliminary final results



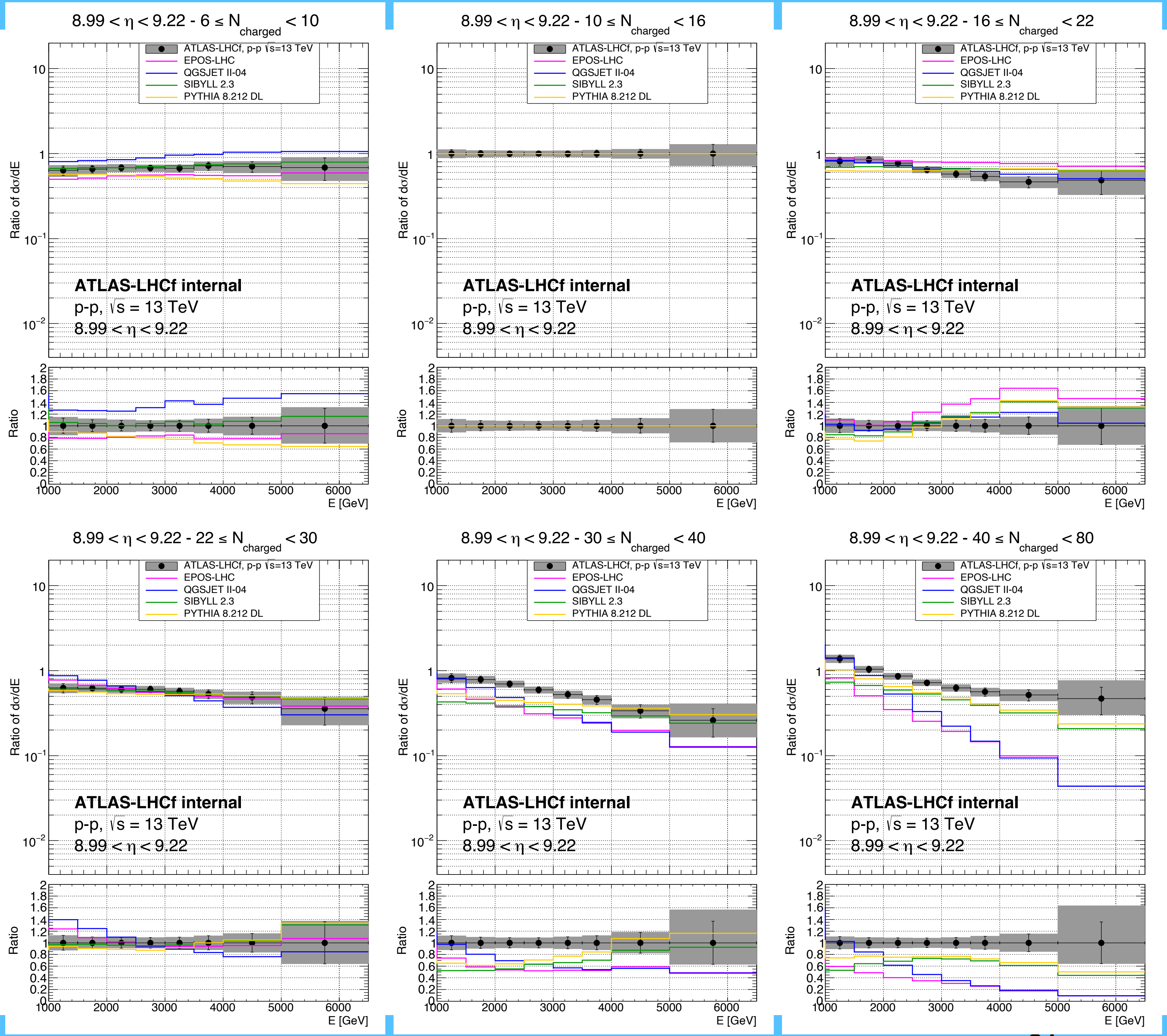


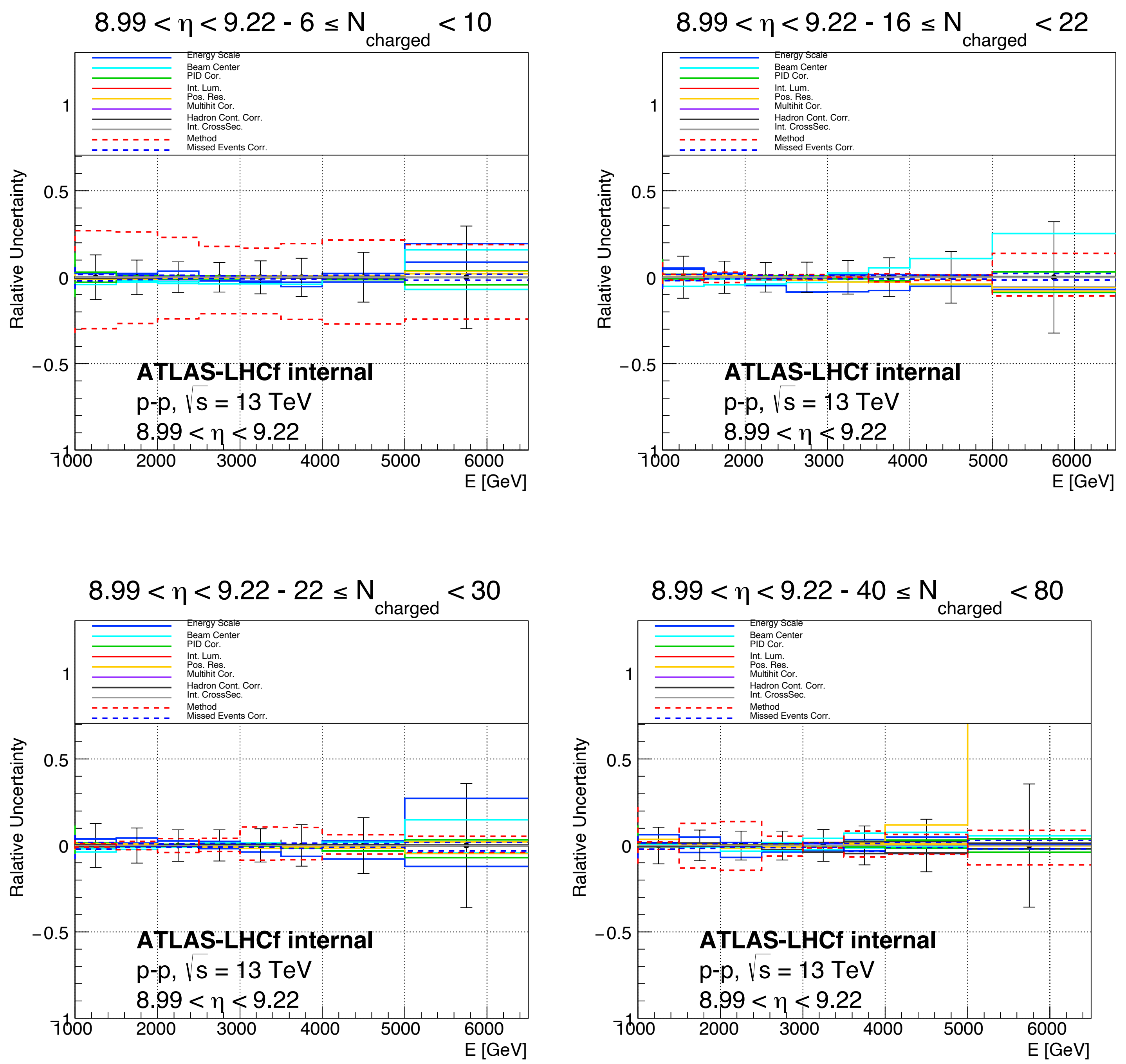
Preliminary final results



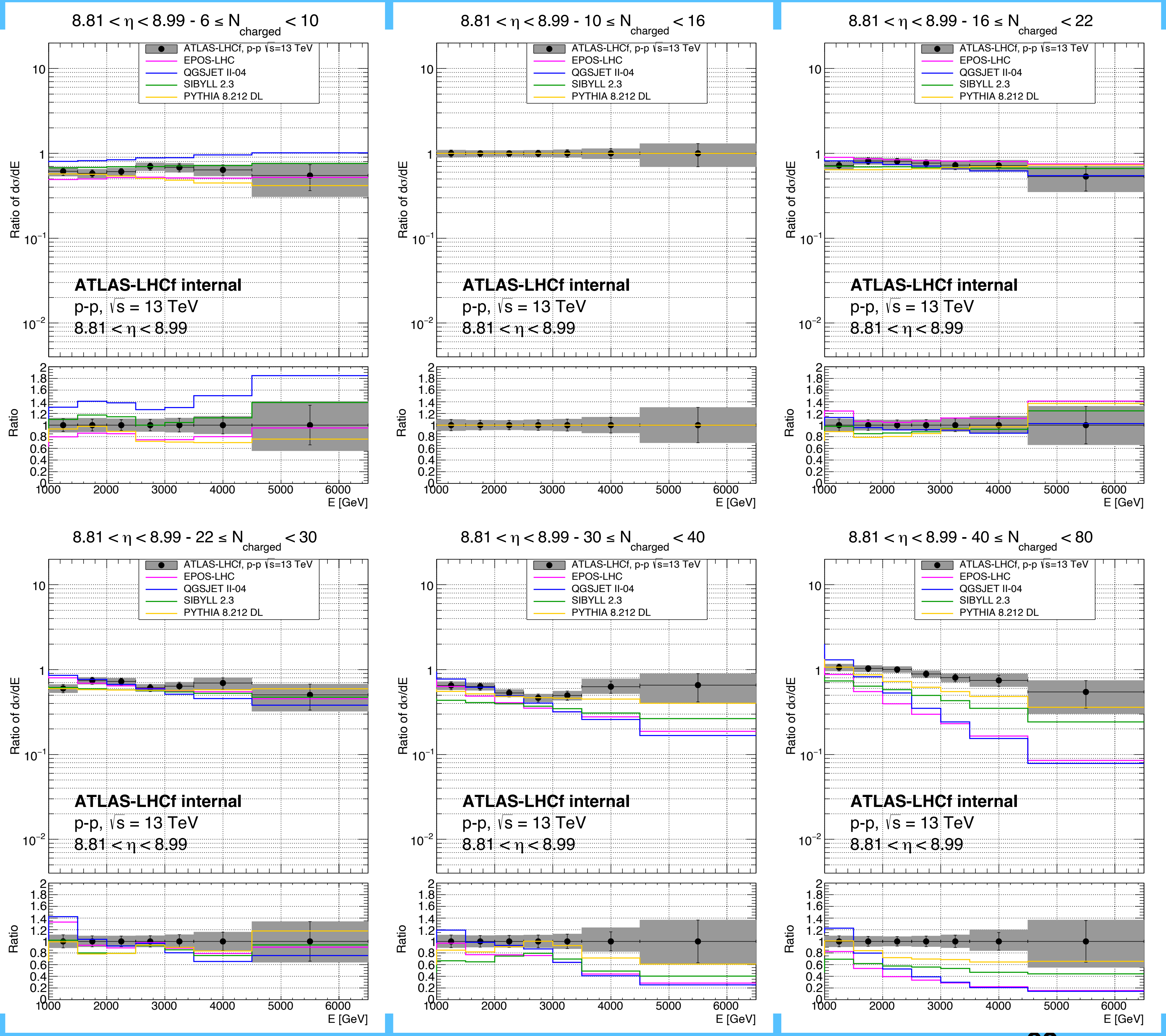


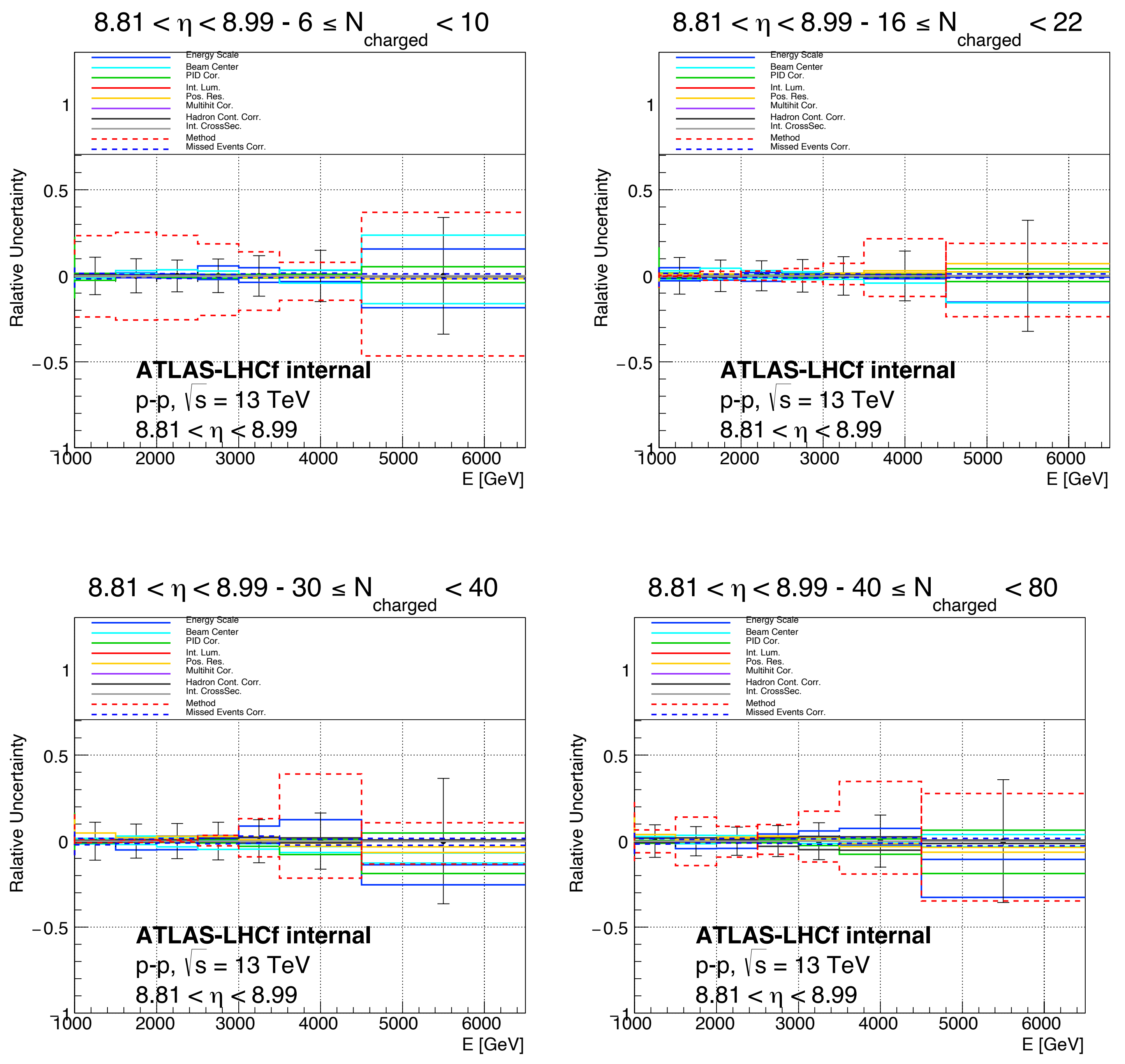
Preliminary final results



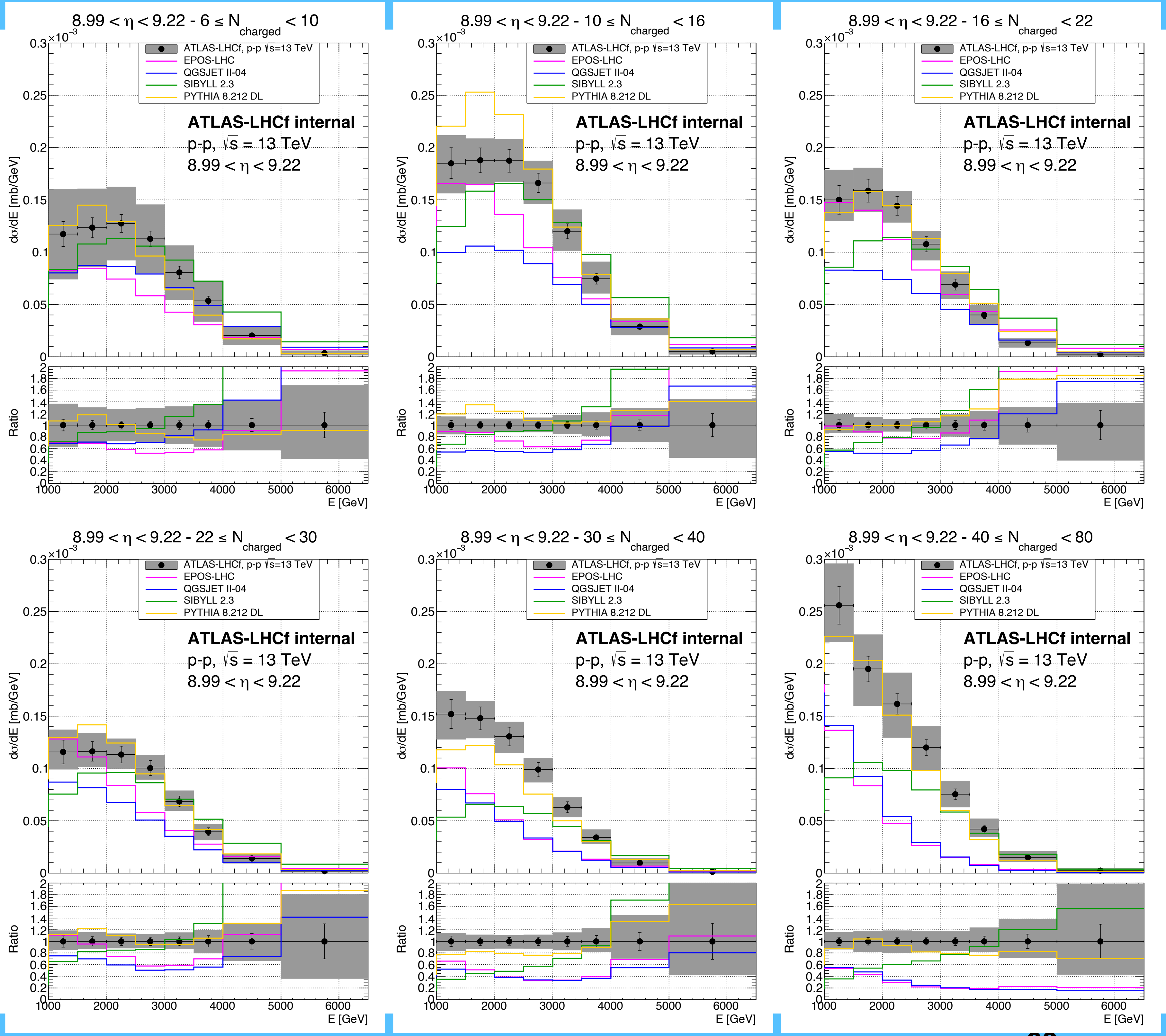


Preliminary final results



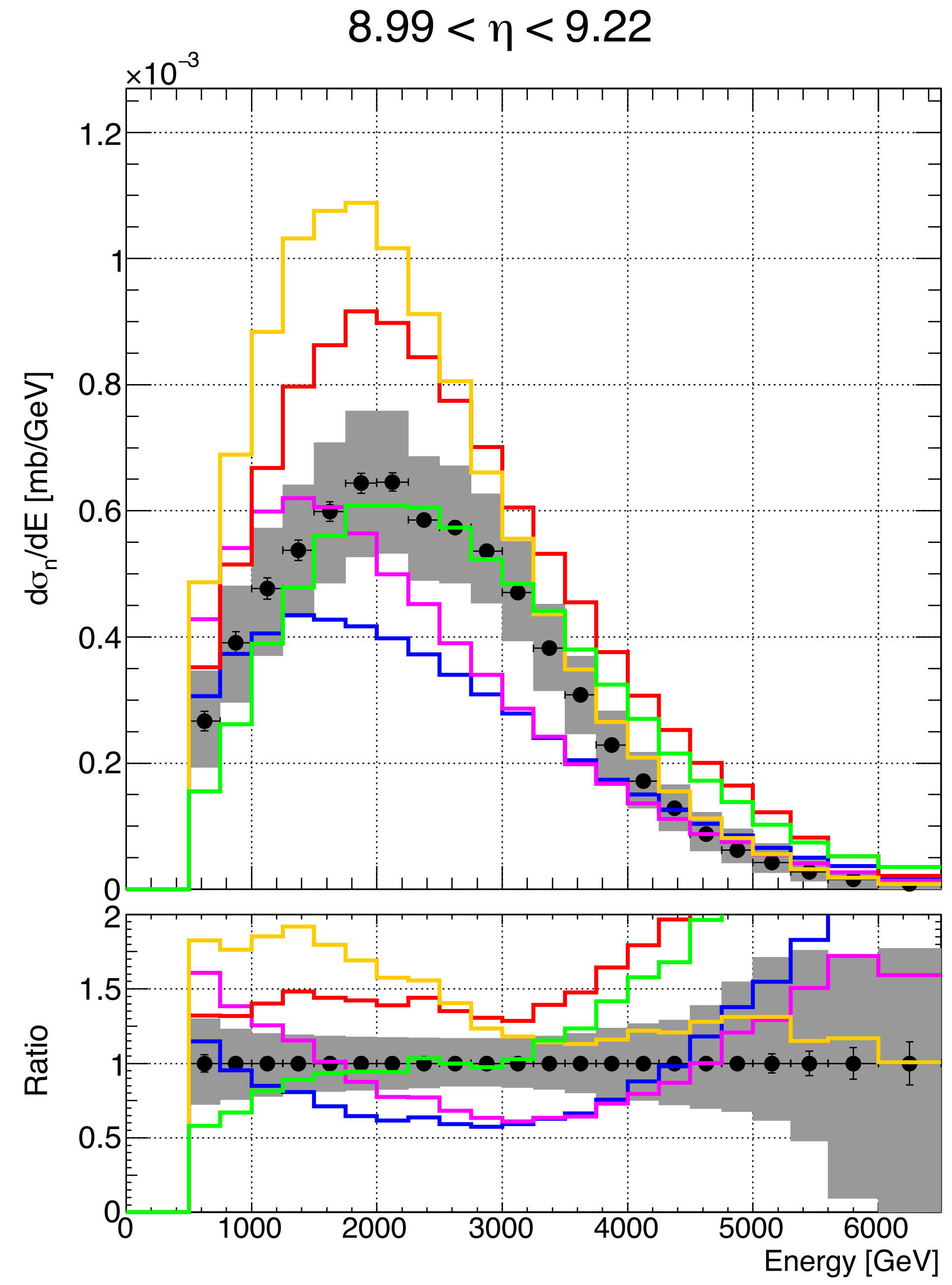


Comparison with LHCf inclusive results

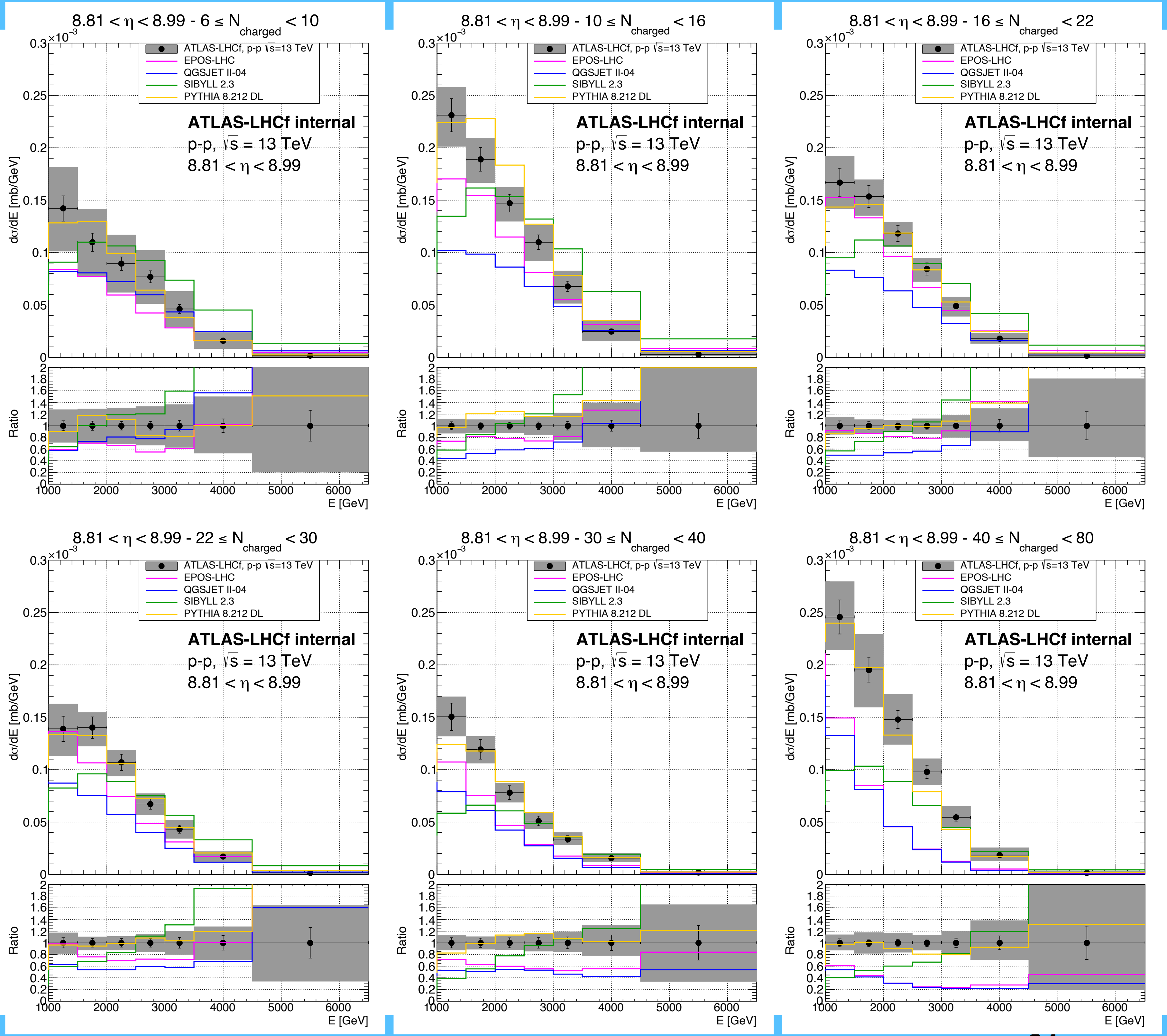


Adriani, O., Berti, E. et al.

J. High Energ. Phys. (2018) 2018: 73

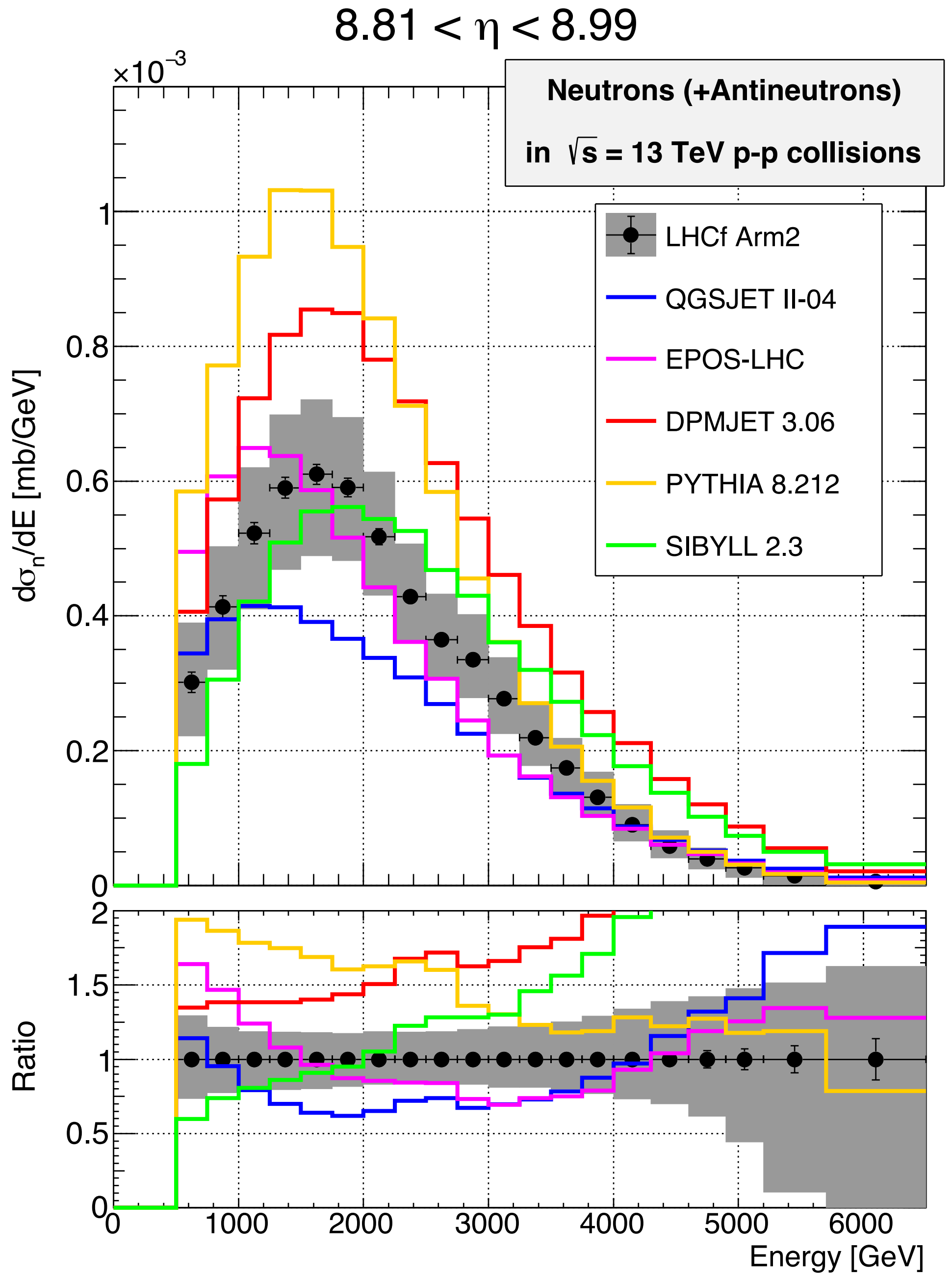


Preliminary final results



Adriani, O., Berti, E. et al.

J. High Energ. Phys. (2018) 2018: 73



Summary and remaining works

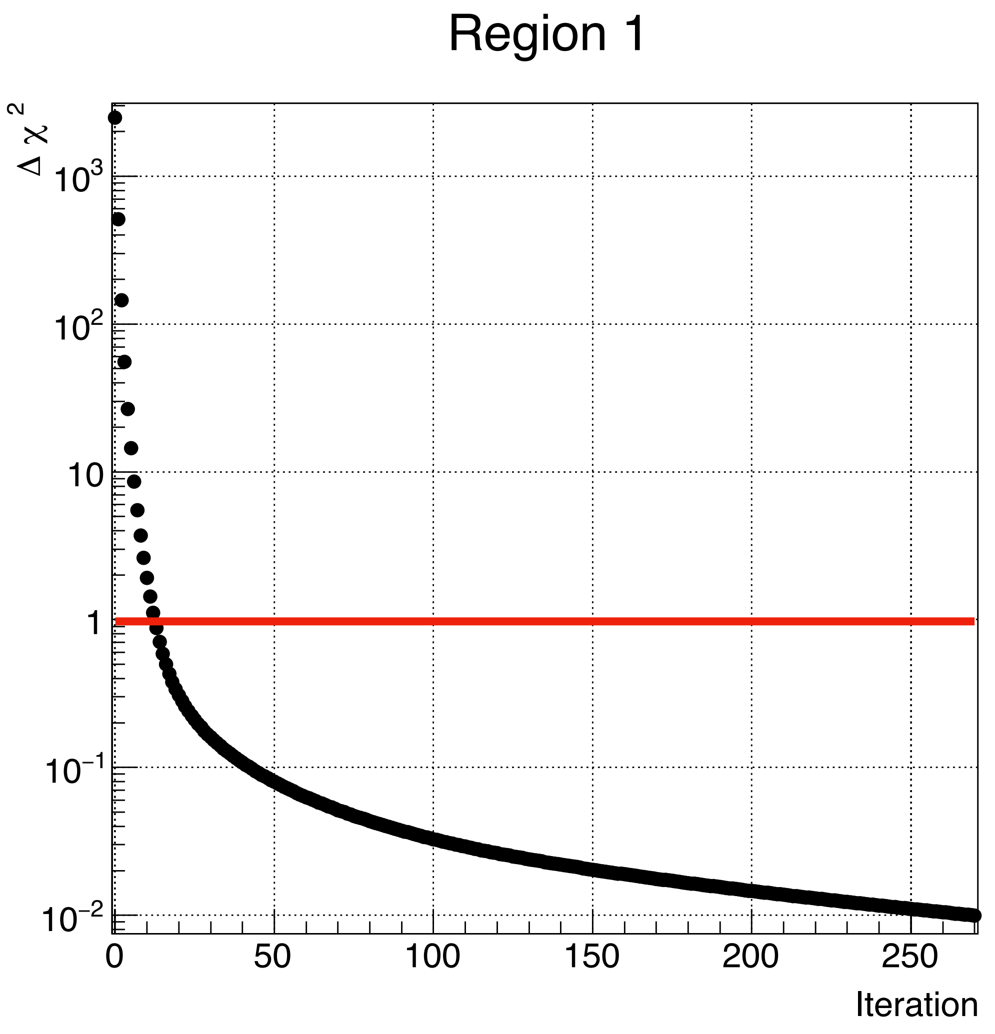
- Finally, we use the MC-driven corrections for multi-hit corrections but with the data-driven tuning of MC simulation.
- We implemented the two-dimensional unfolding.
  - The performance of the unfolding was confirmed by using ATLAS-LHCf common simulation samples instead of experimental data.
  - Propagations of systematic uncertainty before unfolding to unfolded spectrum were considered.
  - We plotted the final plots.
  - Thanks to the correlation of systematic uncertainty, systematic uncertainty in the ratio plots were smaller than statistical errors.
- Remaining works
  - Several minor updates of calculations
  - Validation of all procedures of analysis using ATLAS-LHCf common simulation instead of experimental data.
  - Analysis note
- Ken Ohashi, the main analyzer, leave the LHCf collaboration at the end of this month.
  - K. O. will contribute the documentation even after leaving the collaboration.
  - Working group members try to complete the analysis note as soon as possible.

Back up

Comments in the last soft QCD meetings

Comments in the presentations on 2022 Apr. 25th

- Why the number of iteration is so large?
  - Energy resolution of LHCf detectors for hadrons was 40%, so to correct them, we need more than 10 iteration.
- Why iteration was stopped at $\Delta\chi^2 = 1$? Can we see plateau in $\Delta\chi^2$ plot?
  - For large number of iteration, change of results become smaller while the result become unstable; statistical errors of unfolded spectrum become very large.
  - Thus, in LHCf-Arm2 analysis, we stopped at $\Delta\chi^2 = 1$ to balance the performance and statistical errors.
- Result of performance test for $5 \leq N_{\text{track}} < 140$
  - [TO DO] I will do it later.



Comments related to fiducial volume / multi-hit

Comments in the presentations on 2022 Apr. 25th

- Why you don’t show $N_{\text{track}} < 10$?
  - We removed $N_{\text{track}} = 0$ due to difficulty in multihit correction.
  - For $2 \leq N_{\text{track}} < 10$, we did unfolding but not shown since some contamination of diffraction may affect results.
  - [TO DO] Solution : show $5 < N_{\text{track}} < 10$
- Another definition of energy spectrum to avoid uncertainty in multihit corrections
  - For example, hadrons in Region 1 but with photon or hadrons in Large tower regions are not removed.
  - Solution : add one spectrum with definition including multihit events?
    - We need to consider new definition carefully.
    - [TO DO] I will try to do it later.
- Effects of multi-hit events (two or more particles in one small calorimeter tower.)
  - These events change the energy spectrum, because two or more particles were reconstructed as one particle.
  - How often? — ~10%.
- Cross-check of multi-hit data-driven method
  - Comparison with MC-driven method / Estimation using MC instead of data.
  - [TO DO] I will report them in the next report or in the document.

Others

- MC in final plots: why PYTHIA is not shown in the final plot
    - Shown in the next pages
- Cross-check of LHCf trigger efficiency
    - Using MBTS or random trigger??
    - For Run3, we can check using ATLAS-ZDC behind the LHCf detector.
    - No solution for the moment.

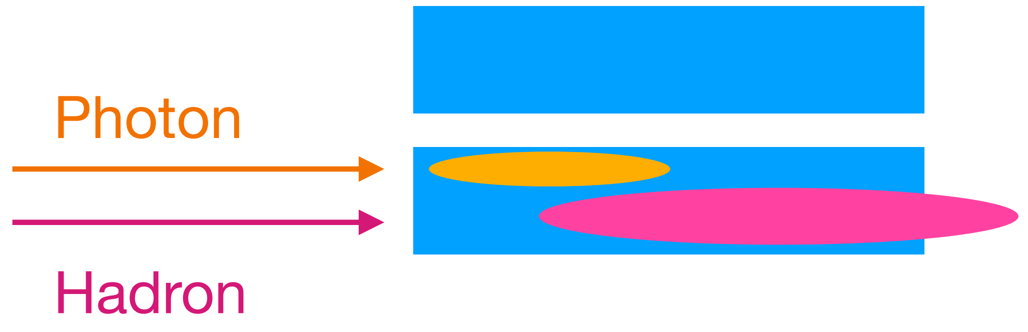
Comments in the presentations on 2022 Apr. 25th

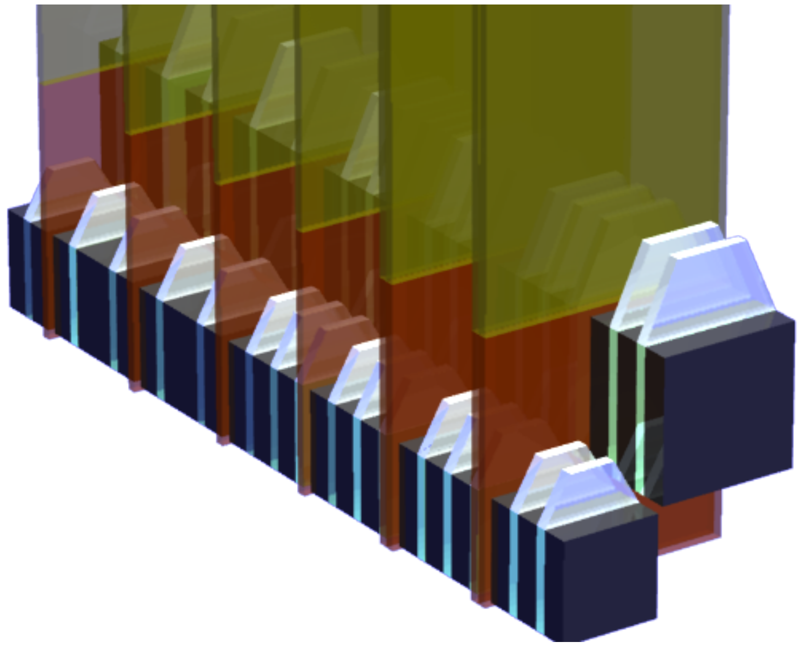
Validation of hadron-tungsten interactions

Idea to validate MC predictions

Using the longitudinal development

- Validation of fractions of non-interacting hadrons
  - Parts of hadrons pass the detector without interactions.
  - Uncertainty in the inelastic cross-sections is one of the systematic uncertainty.
  - The inelastic cross-section can be validated using the shower start points of hadron events
  - Check the first layer with pass the software trigger.
    - The distributions of the first layer roughly correspond to the start point of the hadronic shower.
  - Distributions of the first layer can be useful to validate inelastic cross-sections between hadrons and tungstens.



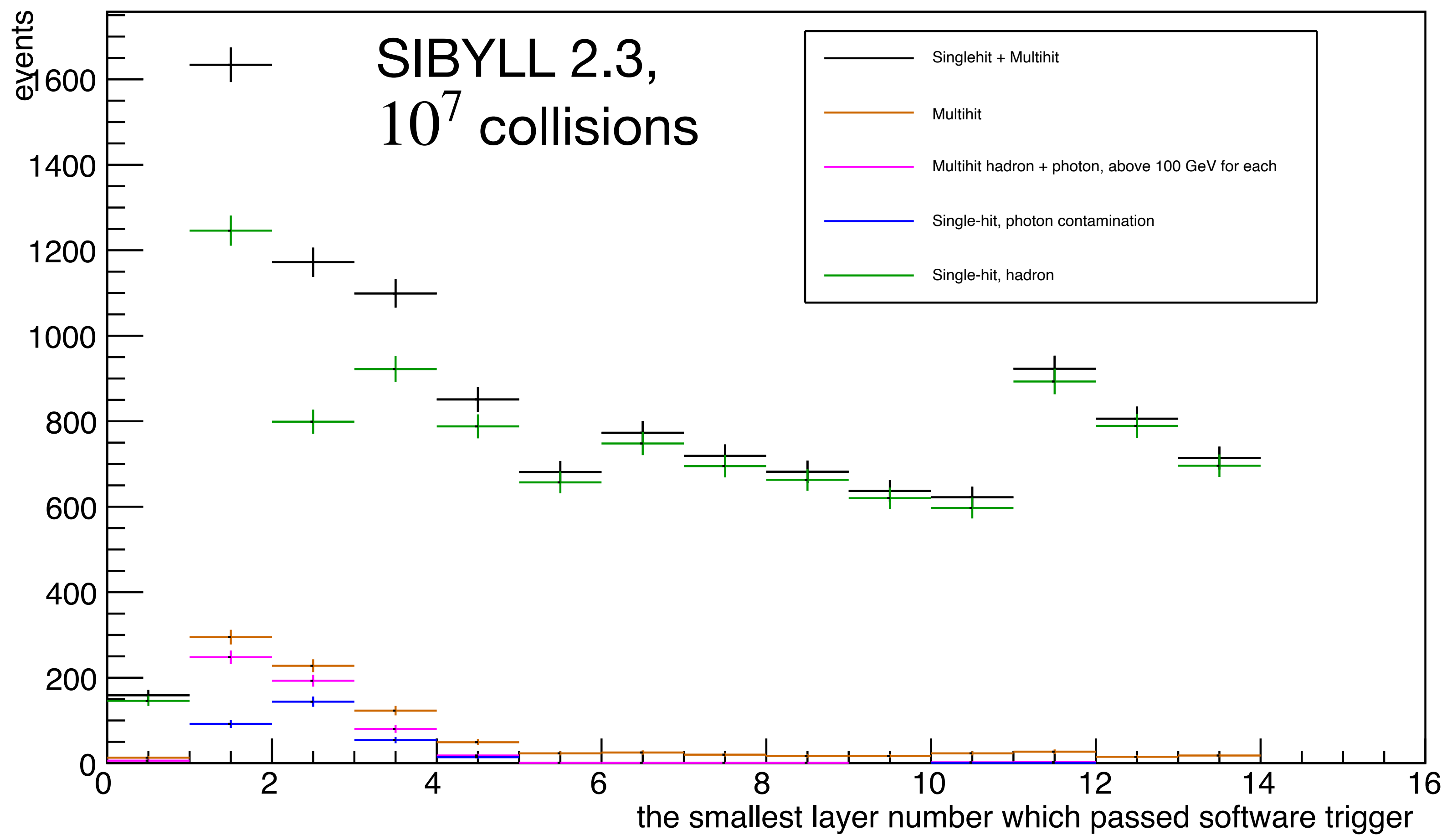


Position sensitive layers before layer 2/5/8
=> energy deposits in layer 2,5,8 were affected.
(Larger gaps between tungsten and scintillator.)

Validation of hadron-W interactions

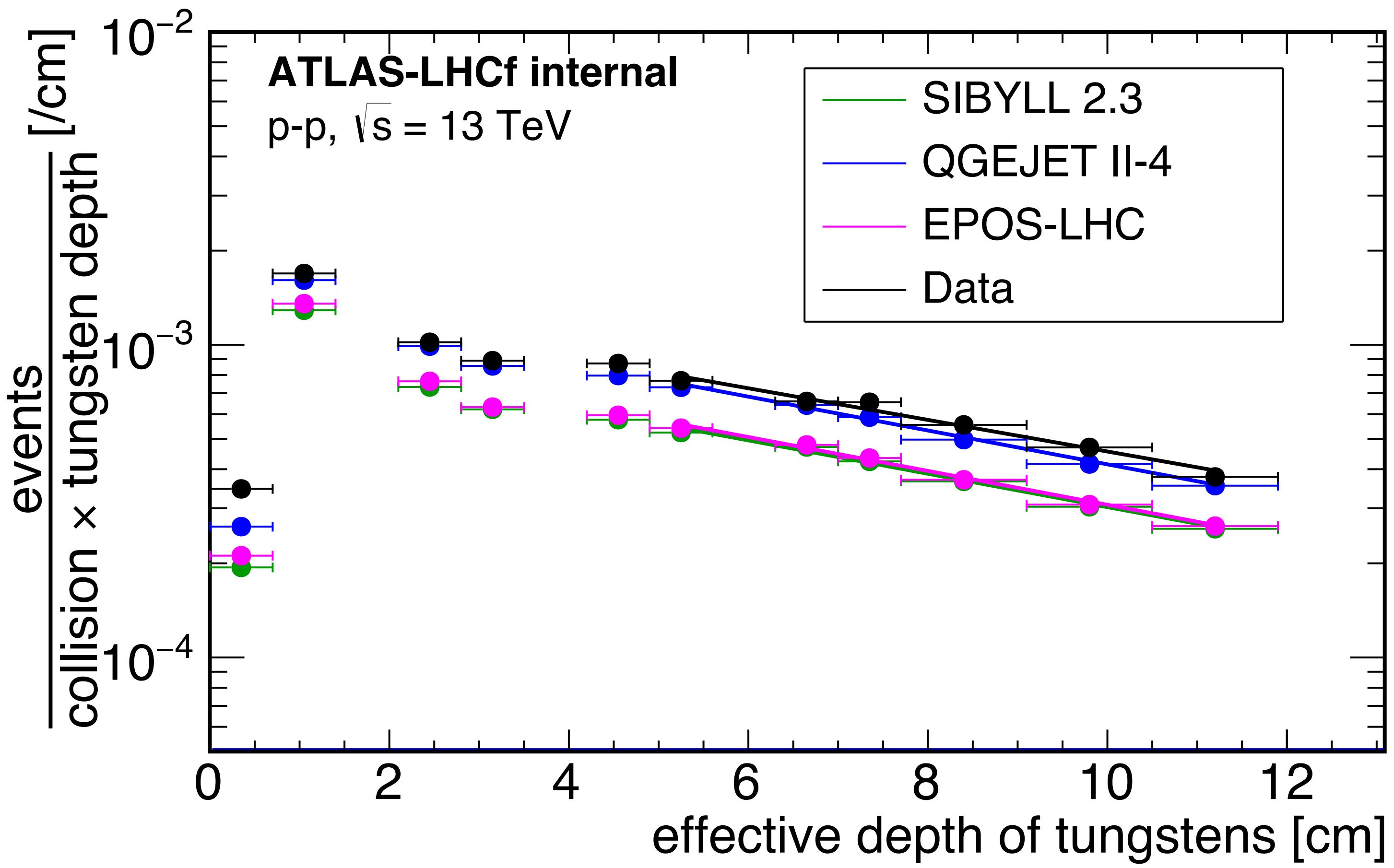
Using the number of events in deeper layers

- For each event,
  - Check the layers passed the software trigger
  - Pick-up the first layer in the passed layers.
- If the first layer is small, contamination of multi-hit and photon events is expected.
- If we focus on the events that started after the 7th layer, we can check the shower start points for single hadron or hadron+hadron multi-hit events.
- Position-sensitive layers are installed before the 3rd, 6th, and 9th layers and between tungsten plates for deeper layers.
  - Energy deposit in the 3rd, 6th, and 9th layers were affected by position-sensitive layers right before the scintillator.



Shower start points as a function of the effective tungsten depth

- Event selection
  - Reconstructed hit in Region 0
  - Passed software trigger
  - $L_{2D} > 25$
- The effective number of events started in the tungsten plates between layers.
  - Remove the layers with the position-sensitive layers just before the scintillation plate.
- Fit
  - From 8th layer to 14th layer
  - $N = a \exp(-x/\Lambda)$
  - Fit results of Λ
    - Data: 8.59 +/- 1.02
    - QGSJET: 8.03 +/- 0.91
    - EPOSLHC: 8.02 +/- 0.92
    - SIBYLL: 8.14 +/- 0.93
- Ratio of Data to MC
  - QGSJET 1.07 +/- 0.18
  - EPOSLHC 1.07 +/- 0.18
  - SIBYLL 1.06 +/- 0.17



Summary of validation of hadron-W interactions

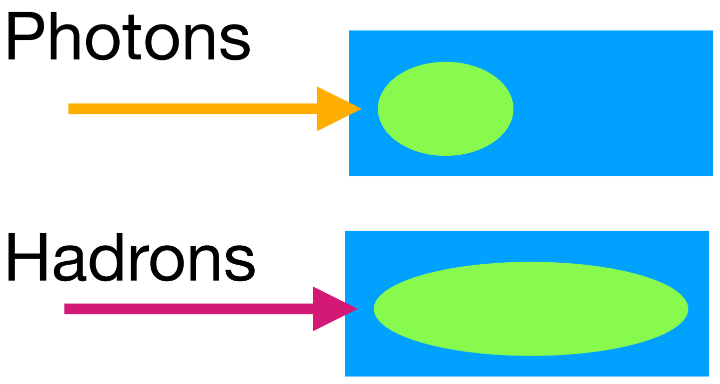
Using the shower start points

- Parts of hadrons pass the detector without interactions. Uncertainty in the inelastic cross-sections is one of the systematic uncertainty.
- The inelastic cross-section can be validated using the shower start points of hadron events
    - If we focus on the events that started after the 7th layer, we can check the shower start points for single hadron or hadron+hadron multi-hit events.
    - The first layer in layers passed the software trigger is roughly correlated with the shower start points.
    - The number of events of the first layer was calculated with effective tungsten depth.
    - The distributions were fitted $N = a \exp(-x/\Lambda)$ from the 8th layer.
- The exponential slope Λ was consistent between data and MC, but the statistical errors of data were large.
    - But this is the only possibility of the validation for the moment.

Analysis

Correction factor

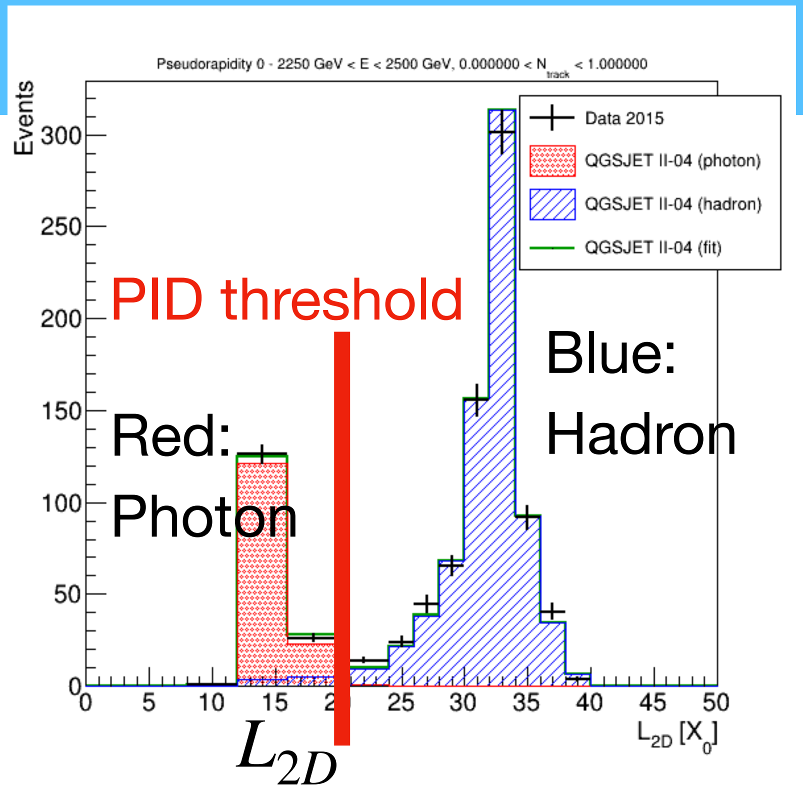
Particle ID **Data + MC (fitting)**



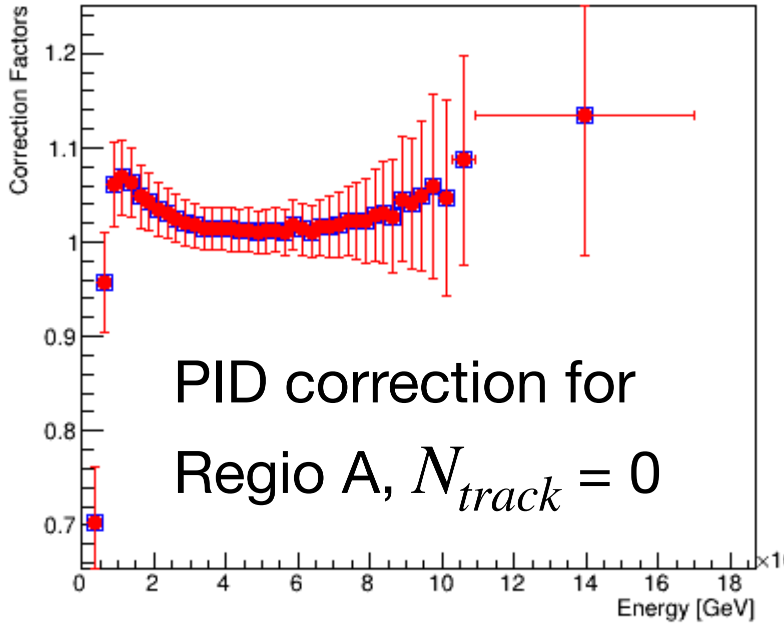
Template fitting of experimental data

Purity and efficiency of PID event selection

PID correction factor



Parameter of the depth of the shower developments.

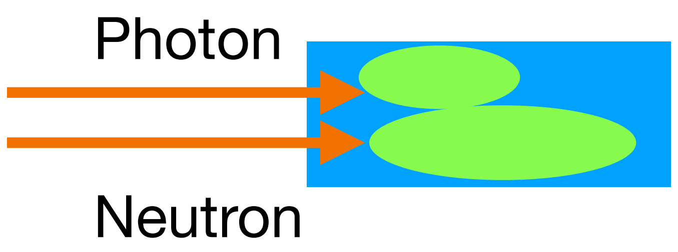


Reconstructed energy [GeV]

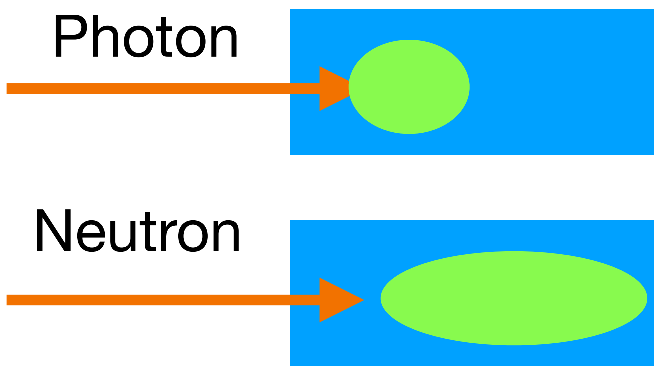
Multi-hit **MC driven -> Data-driven**

Correction was calculated using two simulation:

Simulation (observed)



Simulation (ideal)



Compare two energy spectra

Multi-hit correction factor

Correction factor

Position migration, fake/miss

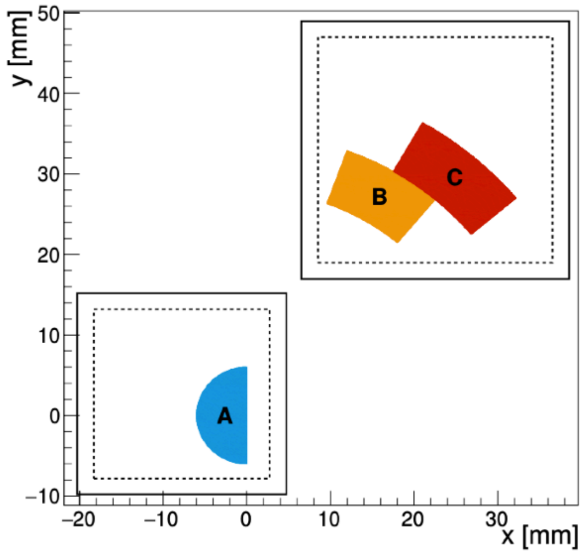
MC driven

Position migration

Migration due to the position resolution

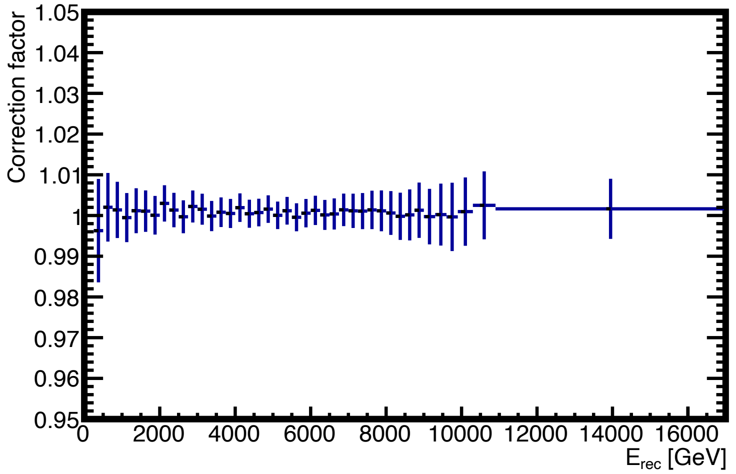
Position resolution; 100 μm for > 3TeV

Three analysis region



Position migration correction for

Region A, $N_{track} = 0$



Reconstructed energy [GeV]

Fake correction

Fake events due to 250 GeV energy cut and energy resolution.

Miss correction (apply after unfolding)

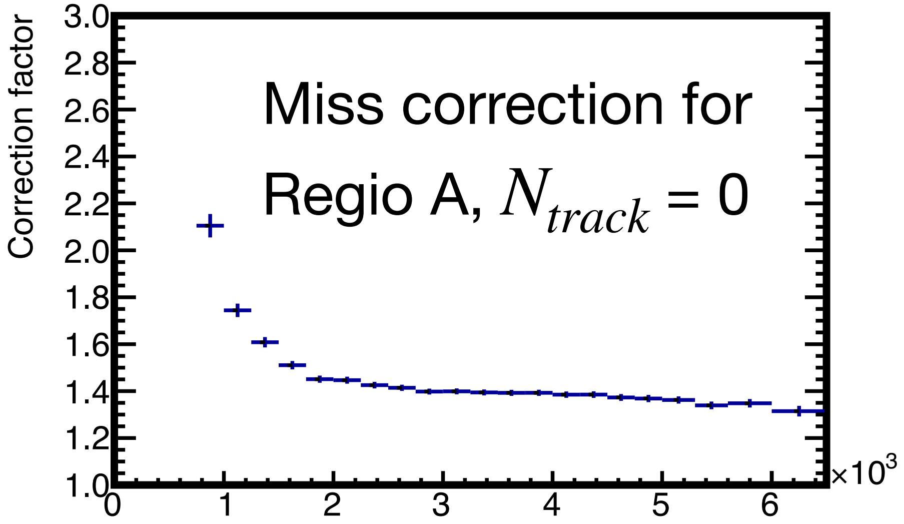
Events without interactions in the detector.

(LHCf detector: 1.6 interaction length,

~ 20-30% events are without interactions

at high energy)

And miss events due to energy threshold cut



True energy [GeV]

Correction factor

Decay in beam pipe **MC driven**

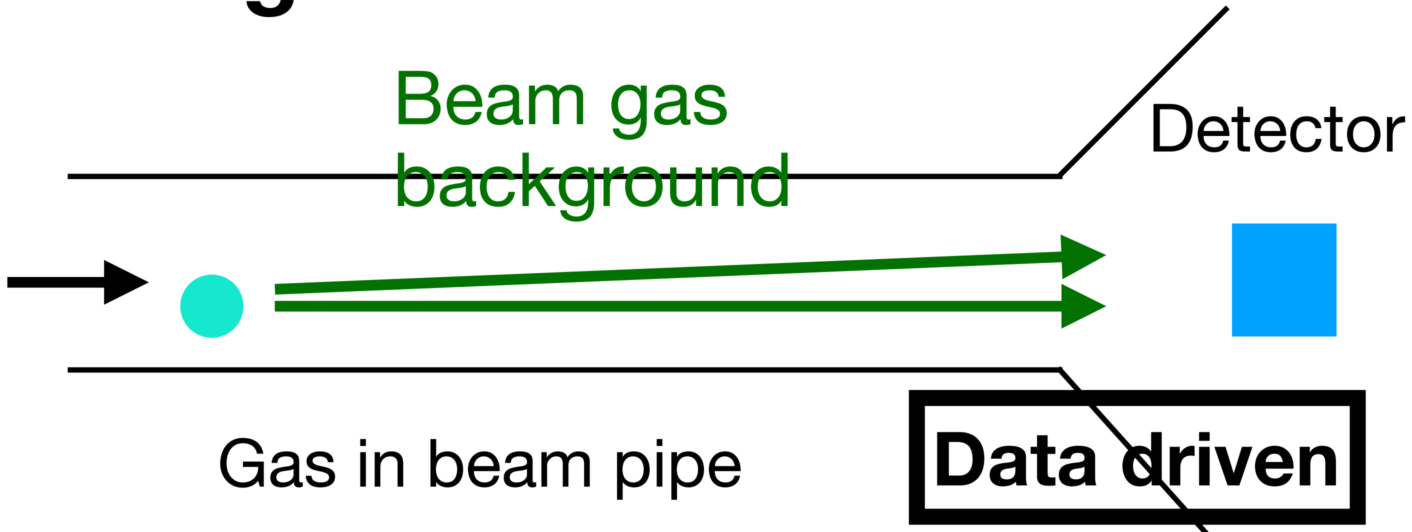
K0, lambda decay

Not applied yet. It is better to show neutral hadrons at 140 m from the interaction point.

ATLAS inner tracker related background correction inner tracker correction

=> Corrected in unfolding.

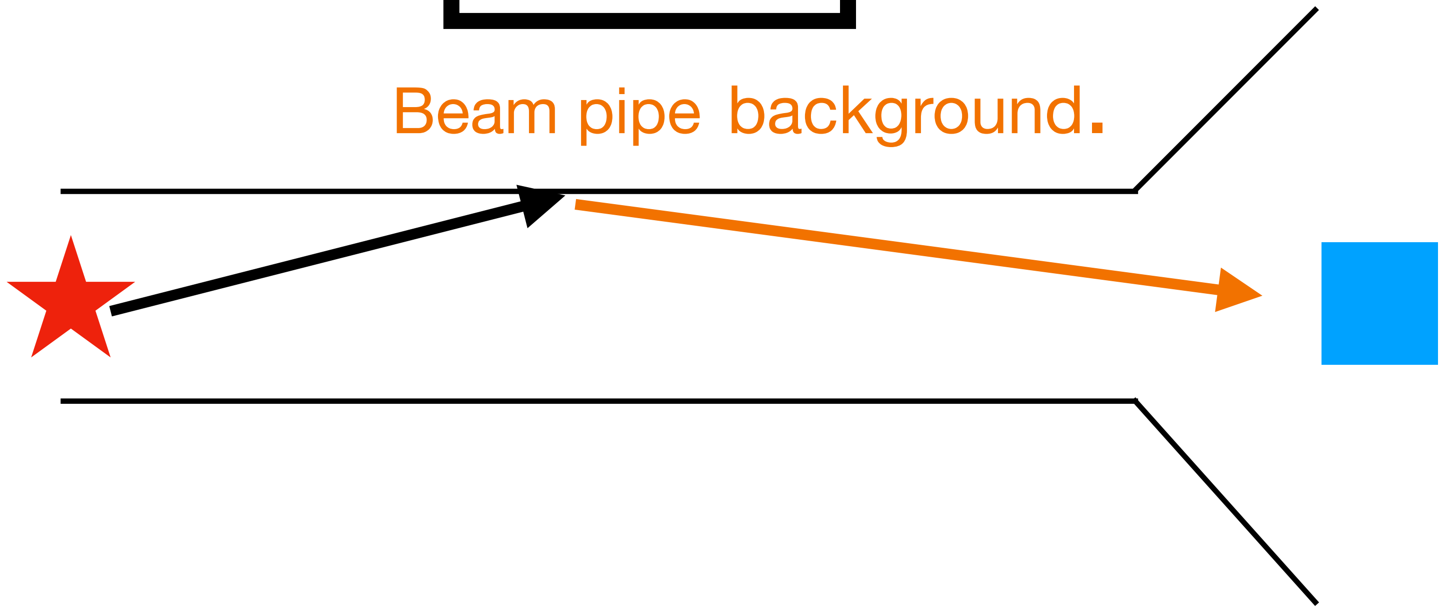
Background Correction



Gas in beam pipe

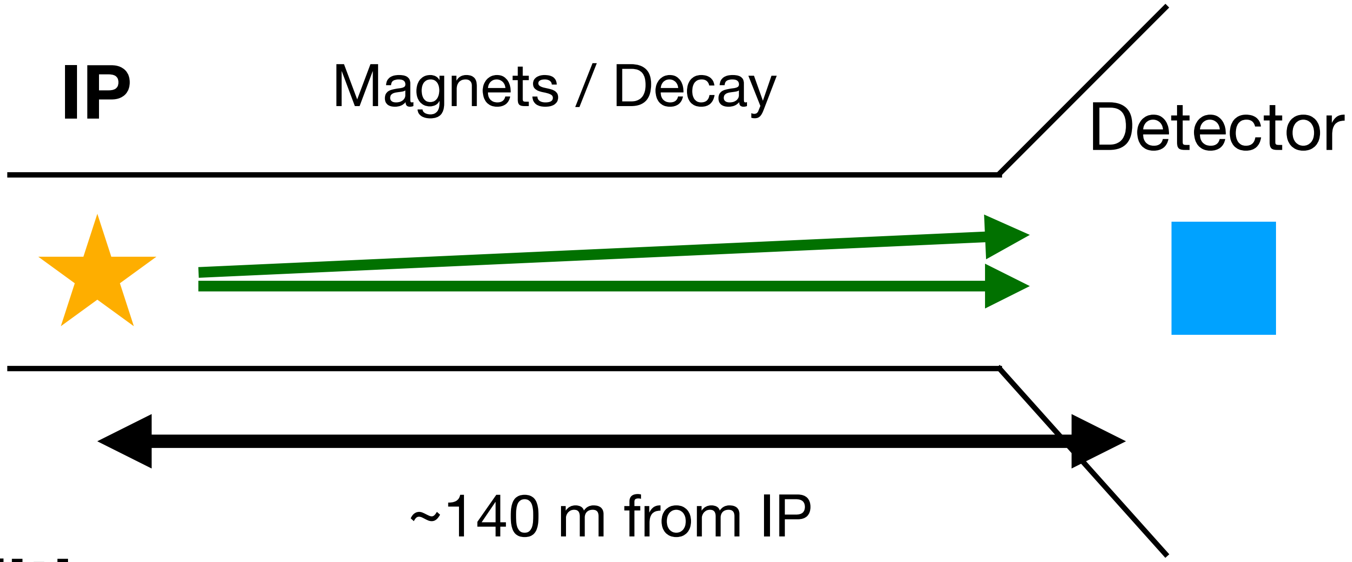
Estimated using non-colliding bunch

MC driven



Correction of effects in beam pipe

Apply corrections for kaon and lambda?



Several possibilities :

a) Neutrons and antineutrons at IP (used in published LHCf results)
   - Corrections of contaminations and decay

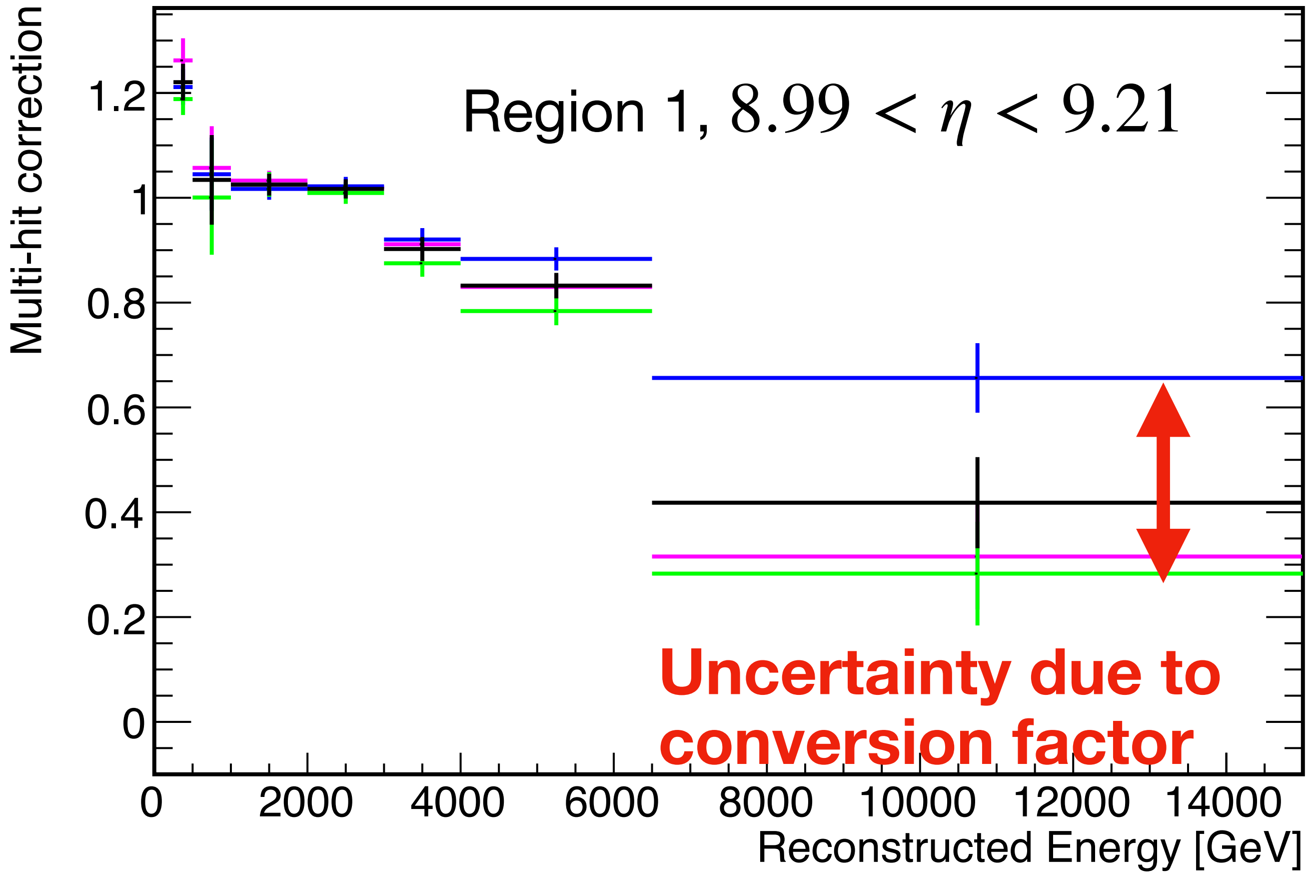
b) Neutral kaon, lambda, neutron, and their antiparticles at IP
   - Corrections of decay

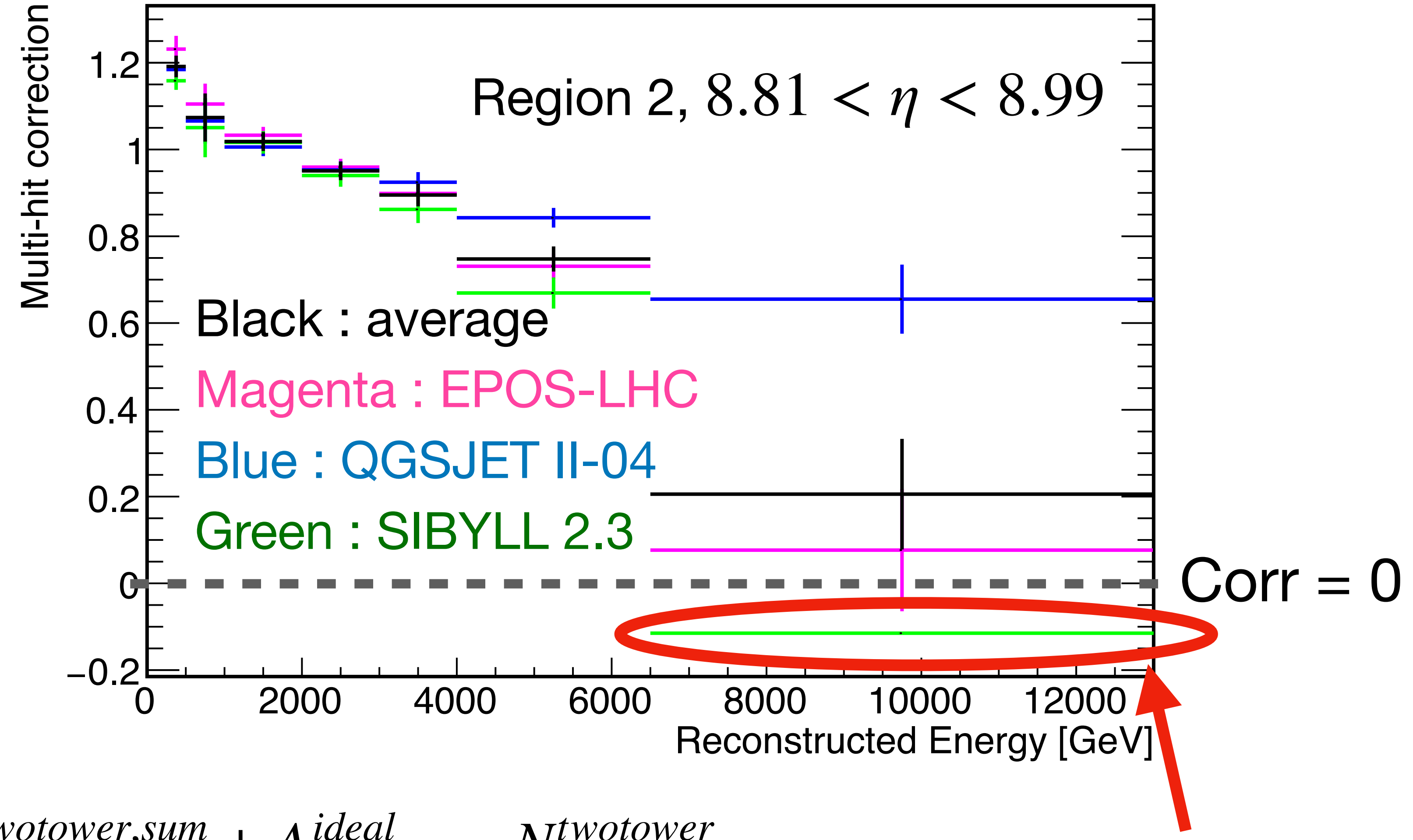
c) Neutral hadrons at 140 m from IP — adopted in this analysis.
   - Small correction
   - In the LHCf simulation, contamination of charged pions at 2-3TeV was simulated.
   - We are checking the simulation.

Data-driven method

Correction should be >0, but smaller than 0 for some case…

Correction factor, three cases using different conversion factor (color lines) and average (black line)





$$C_i^{MH} = \frac{N_{data,i}^{N_{\text{charged}}\geq 2} - A_{conversion,i}^{observed} N_{data,i}^{twotower,sum} + A_{conversion,i}^{ideal} N_{data,i}^{twotower}}{N_{data,i}^{N_{\text{charged}}\geq 2}}$$

(100-102*1.17 + 2*3.86)/100

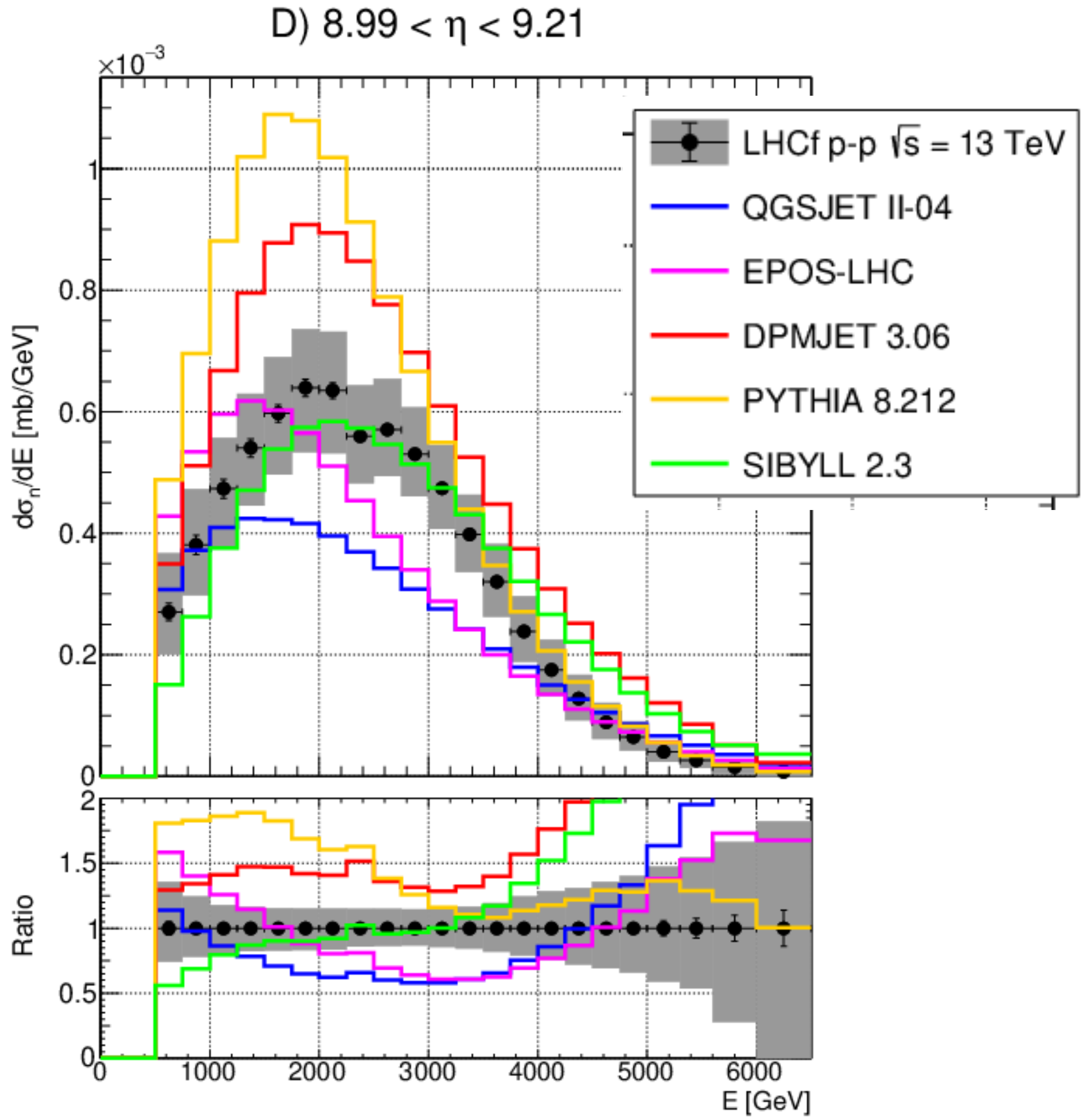
At the highest energy bin, the number of multi-hit events estimated from two-tower events is larger than spectrum (single-hit + multi-hit).

Motivation 2 : for cosmic-ray physics

Better understanding of forward neutron productions

- Understandings of very forward particles are very important for cosmic-ray physics.
- SIBYLL 2.3 (green line) looks better than EPOS-LHC (magenta line) and QGSJET II-04 (blue line).
    - But MPI mechanism which explained in the previous page affects this spectrum.
    - Diffractive dissociation also affects this spectrum.
    - In ATLAS-LHCf joint analysis, we can compare energy spectrum with the number of charged particles in $|\eta| < 2.5$.
- In this analysis we focus on $N_{\text{charged}} \geq 10$, where contributions of diffractive dissociation are negligible.

LHCf neutron spectrum (*JHEP* 2007 (2020) 016)



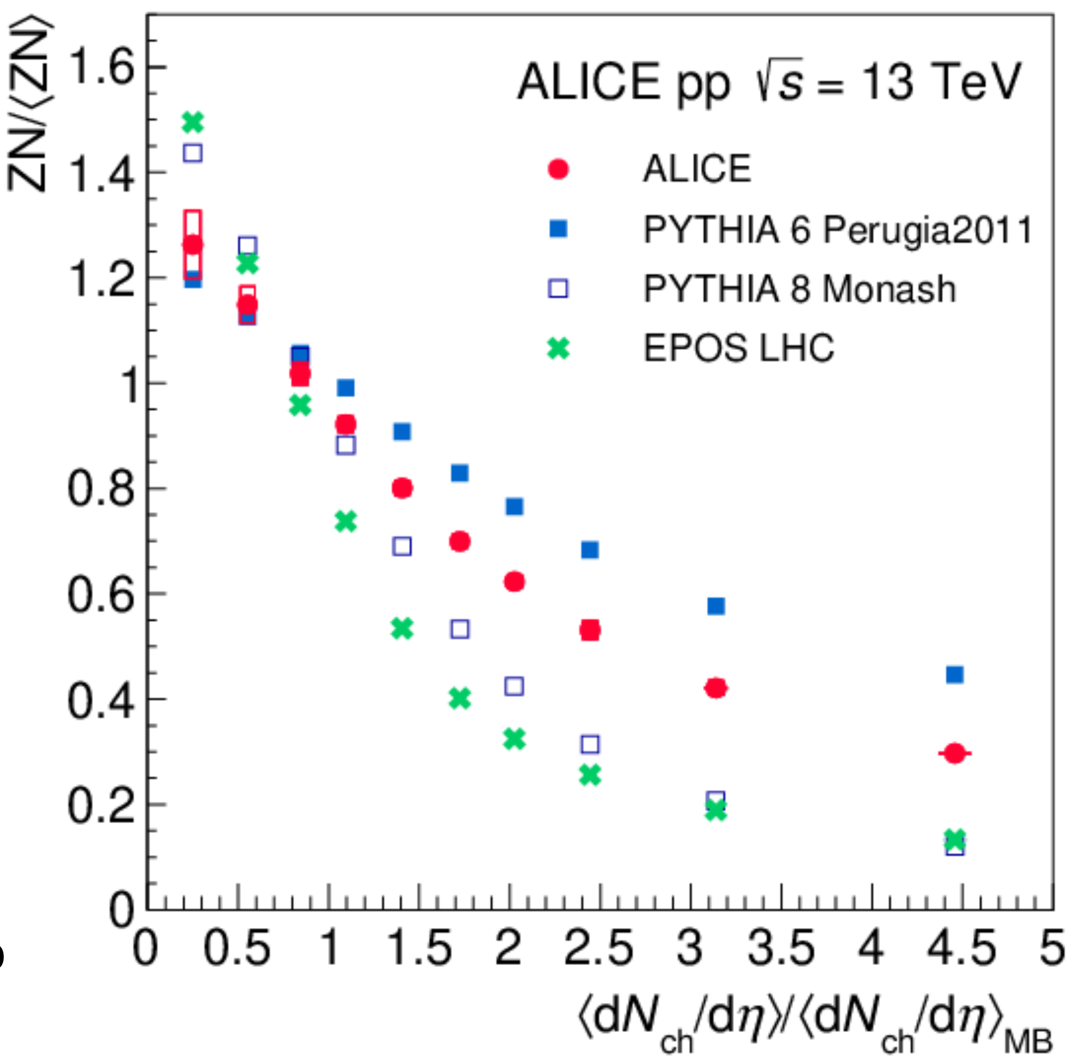
Recent paper by ALICE-ZDC

Similar study was performed by ALICE-ZDC (arXiv : arXiv:2107.10757)

- Using ALICE-ZDC, they show correlation between multiplicity in $|\eta| < 1$ and forward signals.
  - Neutron modules of the ALICE-ZDC cover $|\eta| > 8.8$.
    - Proton modules cover $6.5 < |\eta| < 7.4$.
  - They do not convert signals to energy, but normalize signals by the mean of signals with minimum-bias measurements.
  - Differences between models are caused by MPI mechanism.
- Advantage of ATLAS-LHCf measurements
  - We can measure forward neutron energy, so we can compare energy spectrum with selections by multiplicity.

ALICE results, arXiv:2107.10757 / CERN-EP-2021-144

Ratio of ZDC signals to mean of ZDC signals in minimum-bias measurements



Ratio of mean of the number of charged particles to minimum-bias measurements